Investigation of a Rotor System Incorporating a Constant-Lift Tip

(NASI-IR-166261) INVESTIGATION OF A ROTOR SYSTEM INCORPORATING A CONSTANT LIFT TIP
Final Contractor Report (Boeing Vertol Co., Philadelphia, Pa.) 326 p HC A15/MF A01

M.A. McVeigh
H. Rosenstein
K. Bartie
F.J. McHugh

Boeing Vertol Company

CONTRACT NAS2-10769
October 1981
Investigation of a Rotor System
Incorporating a Constant-Lift Tip

M.A. McVeigh
H. Rosenstein
K. Bartie
F.J. McHugh

Boeing Vertol Company
P.O. Box 16858
Philadelphia, Pennsylvania 19142

Prepared for
Ames Research Center
Under Contract NAS2-10769

NASA
National Aeronautics and Space Administration
Ames Research Center
Moffett Field, California 94035
Abstract

A wind tunnel test of a 16.8 ft. model of a rotor having passively controlled pivotable tips is described. Performance and vibratory hub load data are presented which compare the performance of the rotor with the tips free and fixed. A brief analysis of the experimental findings is included.
TITLE: Investigation of a Rotor System Incorporating a Constant-Lift Tip

ORIGINAL RELEASE DATE: FOR THE RELEASE DATE OF SUBSEQUENT REVISIONS, SEE THE REVISION SHEET. FOR LIMITATIONS IMPOSED ON THE DISTRIBUTION AND USE OF INFORMATION CONTAINED IN THIS DOCUMENT, SEE THE LIMITATIONS SHEET.

MODEL: ________________ CONTRACT: ________________

ISSUE NO.: ___________ ISSUED TO: ____________________

PREPARED BY: M. A. McVeigh/K. Bartie DATE: 30 Oct 81
APPROVED BY: J. Rosenstein DATE: 30 Oct 81
APPROVED BY: J. McHugh DATE: ____________________
LIMITATIONS

This document is controlled by Preliminary Design Aerodynamics - 7441

All revisions to this document shall be approved by the above noted organization prior to release.
<table>
<thead>
<tr>
<th>LTR</th>
<th>DESCRIPTION</th>
<th>DATE</th>
<th>APPROVAL</th>
</tr>
</thead>
</table>

FORM 40210 (3/67)
FOREWORD

The work reported in this document was performed by the Boeing Vertol Company for the National Aeronautics and Space Administration - Ames Research Center under Contract NAS2-10769 during the period December 1980 through October 1981.

The NASA Technical Monitor was Mr. Robert H. Stroub, and the Boeing Program Manager was Mr. Harold Rosenstein. The Boeing Project Engineer was Mr. Michael A. McVeigh.
ABSTRACT

A wind tunnel test of a 16.8 foot model of a rotor having passively-controlled pivotable tips is described. Performance and vibratory hub loads data are presented, which compare the performance of the rotor with the tips free and fixed. A brief analysis of the experimental findings is included.
A wind tunnel test of a 16.8 foot diameter model of a free tip rotor is described. The test was conducted at full-scale tip speeds up to an advance ratio of 0.4. Measurements were made of the rotor vibratory hub loads and performance, both with the tips free to operate and with them locked. It was found that the 4/rev vibratory resultant in-plane loads were reduced when the tips were free, but that power required and the vertical 4/rev loads were greater than with the tips locked. Analysis of the data showed that the reduced performance was attributable to the free tip operating at angles of attack well beyond the anticipated value. This resulted in excessive tip drag and increased power.

Detailed performance data and cross plots of this data are presented in appendices.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOREWORD</td>
<td>iv</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td>SUMMARY</td>
<td>vi</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>x</td>
</tr>
<tr>
<td>1.0 INTRODUCTION</td>
<td>1.1</td>
</tr>
<tr>
<td>2.0 MODEL DESCRIPTION</td>
<td>2.1</td>
</tr>
<tr>
<td>3.0 DATA ACQUISITION</td>
<td>3.1</td>
</tr>
<tr>
<td>4.0 TEST PROCEDURE AND CONDITIONS</td>
<td>4.1</td>
</tr>
<tr>
<td>5.0 TEST RESULTS AND ANALYSIS</td>
<td>5.1</td>
</tr>
<tr>
<td>6.0 CONCLUSIONS AND RECOMMENDATIONS</td>
<td>6.1</td>
</tr>
<tr>
<td>7.0 REFERENCES</td>
<td>7.1</td>
</tr>
<tr>
<td>APPENDIX A TEST DATA</td>
<td>A-1</td>
</tr>
<tr>
<td>APPENDIX B CROSS PLOTS</td>
<td>B-1</td>
</tr>
<tr>
<td>Figure No.</td>
<td>Title</td>
</tr>
<tr>
<td>-----------</td>
<td>--------------------------------------------------------</td>
</tr>
<tr>
<td>1.1</td>
<td>Schematic of Free-Tip Concept</td>
</tr>
<tr>
<td>2.1</td>
<td>Constant Lift Tip Schematic</td>
</tr>
<tr>
<td>2.2</td>
<td>Model in Test Section</td>
</tr>
<tr>
<td>2.3</td>
<td>Free Tip</td>
</tr>
<tr>
<td>3.1</td>
<td>Force and Moment Sign Convention</td>
</tr>
<tr>
<td>3.2</td>
<td>Sample Printout</td>
</tr>
<tr>
<td>4.0a</td>
<td>Response of Free-Tip to Air Jet in Hover</td>
</tr>
<tr>
<td>4.0b</td>
<td>Test Arrangement for Friction Pull Test</td>
</tr>
<tr>
<td>4.1</td>
<td>Test Run Log</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>Flag Note Summary</td>
</tr>
<tr>
<td>4.3</td>
<td>Component Descriptions</td>
</tr>
<tr>
<td>5.1</td>
<td>Notation</td>
</tr>
<tr>
<td>5.2</td>
<td>Coefficients $a_{ij}$, $A_i$</td>
</tr>
<tr>
<td>5.3</td>
<td>Pivot Screw Geometry</td>
</tr>
<tr>
<td>5.4</td>
<td>Measured Rotor Power Required with Tip Free and Compar-</td>
</tr>
<tr>
<td></td>
<td>ison with Theory</td>
</tr>
<tr>
<td>5.5</td>
<td>Variation of Figure of Merit with Thrust Coefficient w-</td>
</tr>
<tr>
<td></td>
<td>ith Tip Free and Comparison with Theory</td>
</tr>
<tr>
<td>5.6</td>
<td>Variation of the Tip Angle, $\delta$, and Comparison</td>
</tr>
<tr>
<td></td>
<td>with Analysis</td>
</tr>
<tr>
<td>5.7</td>
<td>Variation of Lift-Curve Slope with Aspect Ratio</td>
</tr>
<tr>
<td>5.8</td>
<td>Variation of Aerodynamic Center with Aspect Ratio</td>
</tr>
<tr>
<td>Figure No.</td>
<td>Title</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>5.9</td>
<td>Comparison of Power Required, Tip Fixed and Free</td>
</tr>
<tr>
<td>5.10</td>
<td>Comparison of Rotor Lift-to-Effective Drag Ratio, Tip Fixed and Free</td>
</tr>
<tr>
<td>5.11</td>
<td>Comparison of Main Blade Collective Pitch, Tip Fixed and Free</td>
</tr>
<tr>
<td>5.12</td>
<td>Tip Response at $u = 0.30$, $C_{T'}/\sigma = 0.0409$</td>
</tr>
<tr>
<td>5.13</td>
<td>Tip Response at $u = 0.30$, $C_{T'}/\sigma = 0.0612$</td>
</tr>
<tr>
<td>5.14</td>
<td>Tip Response at $u = 0.30$, $C_{T'}/\sigma = 0.0843$</td>
</tr>
<tr>
<td>5.15</td>
<td>Tip Response at $u = 0.30$, $C_{T'}/\sigma = 0.1113$</td>
</tr>
<tr>
<td>5.16</td>
<td>Tip Response at $u = 0.30$, $C_{T'}/\sigma = 0.12144$</td>
</tr>
<tr>
<td>5.17</td>
<td>Effect of Tip Weights on Tip Response</td>
</tr>
<tr>
<td>5.18</td>
<td>Comparison of Vertical Vibratory Hub Loads, Tip Fixed and Free</td>
</tr>
<tr>
<td>5.19</td>
<td>Comparison of the Inplane Vibratory Hub Loads, Tip Fixed and Free</td>
</tr>
<tr>
<td>5.20</td>
<td>Development of Low Aspect Ratio Flow at Free Tip</td>
</tr>
<tr>
<td>Table No.</td>
<td>Title</td>
</tr>
<tr>
<td>----------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>2.1</td>
<td>Location of Blade Strain Gauges</td>
</tr>
</tbody>
</table>
1.0 INTRODUCTION

1.1 Basic Concept

The constant-lift tip rotor concept uses a blade tip segment that is passively controlled in pitch in such a way that each tip operates at essentially constant lift as the blade moves around the azimuth. The principle of operation is illustrated by Figure 1.1 which shows a rotor blade whose tip is free to rotate about a pivot.

In order for the tip to operate at essentially constant lift, it is pivoted ahead of its own aerodynamic center, with the blade balanced so that the c.g. lies on the pivot. If a nose-up controlling moment is now supplied to the tip via the pivot, the tip develops positive lift and a nose-down pitching moment that grows until the pivot-supplied moment is cancelled. By designing the pivot mechanism to supply a moment that is constant (independent of azimuth and tip deflection), then the tip is forced to fly at constant lift.

The freedom to rotate ensures that the inboard blade will be isolated from the tip torsional loads. If the tip were so designed that it would operate at a prescribed lift level independent of azimuth, then the tip-induced vertical and torsional vibratory loads would be eliminated. This could contribute significantly to the alleviation of helicopter vibration.

A further benefit of the constant lift feature is a potential improvement in rotor lift-to-effective drag ratio, L/D_e. On a conventional rotor the tip is negatively loaded on the advancing side while maintaining high positive lift on the retreating side. With the constant-lift (free tip) concept, the advancing side is positively loaded, which should improve L/D_e.

1.2 Analytical Studies

A theoretical evaluation of the constant-lift tip rotor is reported in Reference 1. The analysis used was V-7, a modified version of Boeing Vertol Program C-60. The math model incorporated the following features:

1. Blade element theory using airfoil lift, drag, and pitching moment tables that include stall and compressibility.
2. Unsteady aerodynamics effects.
3. Nonuniform downwash based on a prescribed wake.
4. Motion of the free tip obtained by solving tip equation of motion.
FIGURE 1.1. SCHEMATIC OF FREE-TIP CONCEPT
5. Fully-coupled flap/pitch motion of the blade with elastic flap and chord deflections and elastic torsion.

This program was applied to predict the performance of a hypothetical free-tip rotor having the following features:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>25.5 feet</td>
</tr>
<tr>
<td>Chord</td>
<td>1.563 feet</td>
</tr>
<tr>
<td>Tip Span</td>
<td>18.36 inches (6% radius)</td>
</tr>
<tr>
<td>Pivot Location</td>
<td>13% chord</td>
</tr>
<tr>
<td>C.G. Location</td>
<td>13% chord</td>
</tr>
<tr>
<td>Tip Speed</td>
<td>704 ft/sec</td>
</tr>
<tr>
<td>Twist</td>
<td>-8° linear</td>
</tr>
<tr>
<td>(Root-to-Tip)</td>
<td></td>
</tr>
<tr>
<td>No. of Blades</td>
<td>4</td>
</tr>
</tbody>
</table>

The performance was calculated with the tip fixed and free producing the same rotor lift and propulsive force, \( C_{T/L} = .073, \bar{X} = .108 \). The results showed that the free tip required considerably less power than the conventional rotor. At 160 knots the savings was 11% and at 130 knots the percent gain was 24%.

1.3 Rotor Design

On the basis of this projected increase in aerodynamic performance, a feasibility study was made of a constant lift tip rotor system. The study was done in sufficient detail to identify the structural concept, method of attachment and materials. The study was then extended to include the design, fabrication and test of a wind tunnel model of the free tip rotor having a 5% radius free tip. The design effort is reported in Reference (2). The wind tunnel test is described in this report.
2.0 MODEL DESCRIPTION

2.1 Free Tip

An existing four-bladed, 16-foot diameter, Mach-scaled model of the CH-47C rotor was selected for modification to the free tip design. This rotor had been previously modified to test a 4.8 inch (5% radius) tapered tip extension. The tapered tip extension was removed and a steel pitch shaft installed at 13% chord to carry the free tip (see Figure 2.1). The steel shaft had a helical groove cut into it. This groove accepted a cam follower pin which was inserted through the leading edge of the free tip. The pin was held in place by a retaining screw. This arrangement allowed the tip to pivot freely within the limits of the groove and still remain captured by the shaft. To minimize friction, the cam follower pin and groove were lubricated by a dry lubricant. Dry-lube bushings guided the pitching motion of the tip section. Provision was made to lock out the tip motion by removing the cam follower pins and replacing them with locking pins.

2.2 Tip Construction

The free tip had a V23010-I58 airfoil with a 5.8 percent chord tab added to match the basic blade airfoil. The tip was constructed of Nomex core and magnesium spar covered with fiberglass. The upper surface had a 0.0005-inch thick Mylar cover to prevent air transfer from the lower to the upper surface. The spar was provided with one permanently-mounted 1/4-inch diameter tantalum balance weight in the nose and four 3/16-inch diameter holes symmetrically arranged about the pivot line. By inserting tantalum rods in these holes, the tip mass, inertia, and chordwise center-of-gravity could be varied. Table A-1 of Appendix A lists the values of these quantities.

2.3 Tip Instrumentation

The tip pitch shaft on one blade only was provided with flap and chord bending gauges as safety-of-flight instrumentation. The angle of the tip relative to the main blade was measured by a Hall-effect device. This device uses a remote magnetic field to modulate an electric current through a semi-conductor. The source magnet was placed in the moving tip and the sensor bonded to the main blade. The advantage of this method of measuring the tip angle is that there is no signal noise, or wiper pressure friction and wear associated with potentiometer arrangements. One slight disadvantage is the nonlinear (sinusoidal) output of the Hall device, which requires a nonlinear calibration algorithm in the data reduction process.

2.4 Main Blade and Test Stand

The main blade was a 16-foot diameter model CH-47C rotor blade
Figure 2.1 Constant Lift Tip Schematic

Sheet 2.2
having a 6.73-inch chord, a constant V23010-1.58 airfoil, and -9 degrees of linear twist from center of rotation to the tip (r = 8'). The test stand was the Dynamic Rotor Test Stand (DRTS) which incorporates an electrical power supply and a 6-component balance. Figure 2.2 presents a photograph of the complete rotor with free tip and Figure 2.3 presents a close-up of one of the tips. The principal properties of the blade are summarized below.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>8.4 ft.</td>
</tr>
<tr>
<td>No. of blades</td>
<td>4.0</td>
</tr>
<tr>
<td>Chord</td>
<td>6.73 inches (constant)</td>
</tr>
<tr>
<td>Solidity</td>
<td>0.085</td>
</tr>
<tr>
<td>Twist (center of rotation to tip)</td>
<td>-9.45 degrees</td>
</tr>
<tr>
<td>Airfoils</td>
<td>V23010-1.58 (constant)</td>
</tr>
<tr>
<td>Cutout</td>
<td>0.1825R</td>
</tr>
<tr>
<td>Flap Hinge</td>
<td>0.031R</td>
</tr>
<tr>
<td>Weight Moment about Flap Hinge</td>
<td>34.5 ft. lb</td>
</tr>
<tr>
<td>Inertia about Flap Hinge</td>
<td>4.55 slugs ft²</td>
</tr>
</tbody>
</table>

Instrumentation for the main blade consisted of 6 flap bending gauges, 2 chord bending gauges and 1 torsion gauge placed as indicated in Table 2.1. Blade motion about the horizontal and vertical pins was continuously measured by transducers placed at the flap and lag hinges of the instrumented blade.
Figure 2.3  Free Tip
# TABLE 2.1

**LOCATION OF BLADE STRAIN GAUGES**

<table>
<thead>
<tr>
<th>GAUGE</th>
<th>BLADE STATION, % RADIUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flap Bending</td>
<td>12.6</td>
</tr>
<tr>
<td></td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>38.4</td>
</tr>
<tr>
<td></td>
<td>46.2</td>
</tr>
<tr>
<td></td>
<td>53.3</td>
</tr>
<tr>
<td></td>
<td>96.6</td>
</tr>
<tr>
<td>Chord Bending</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>53.3</td>
</tr>
<tr>
<td>Torsion</td>
<td>12.6</td>
</tr>
</tbody>
</table>
3.0 DATA ACQUISITION

The wind tunnel test of a rotor requires the measurement of net rotor forces and moments, rotor control positions and blade loads almost simultaneously. To achieve this, the data is sensed, multiplexed, processed, then stored on magnetic tape and/or printed. Computed results in standard engineering units and coefficient format are tabulated by a line printer and selected variables are plotted by the X-Y plotters. Final data is stored on magnetic tape for additional processing.

A control panel digital display of nine channels of processed data is available for setting up model test conditions and monitoring purposes during the testing. Dynamic data of six quantities is continuously displayed on oscilloscopes to provide assistance in preventing model balance or rotor structural limits from being exceeded.

A data reduction program transforms the electrical signals and calculates the various tunnel parameters to be printed on-line. In addition to these items, the maximum and minimum values, mean value and alternating components of each selected blade load measurement are calculated and tabulated on-line.

Root flap bending, chord bending and torsion loads, as well as root flap and lag angle, are harmonically analyzed up to the first nine harmonics and the results are listed along with the other data. Following the test, waveforms are reconstituted from the dynamic data on the magnetic tapes.

At each test point, measurements are taken for computing and tabulating on-line the quantities listed. The listed balance forces and moments follow the sign convention illustrated in Figure 3.1.

<table>
<thead>
<tr>
<th>(a) Tunnel and Model Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Air density, ( \rho )</td>
<td>slugs/ft(^3)</td>
</tr>
<tr>
<td>Freestream dynamic pressure, ( q )</td>
<td>lb/ft(^2)</td>
</tr>
<tr>
<td>Tunnel velocity (corrected), ( V )</td>
<td>ft/sec</td>
</tr>
<tr>
<td>Tunnel static temperature, ( T_s )</td>
<td>°F</td>
</tr>
<tr>
<td>Rotor advance ratio, ( \mu' = \frac{V}{\frac{R}{R}} )</td>
<td>-</td>
</tr>
<tr>
<td>Rotor collective angle, ( \theta_{.75} )</td>
<td>deg</td>
</tr>
<tr>
<td>Rotor lateral cyclic angle, ( A_{lc} )</td>
<td>deg</td>
</tr>
</tbody>
</table>
Figure 3.1 Force and Moment Sign Convention
(a) **Tunnel and Model Parameters** (continued)

- Rotor longitudinal cyclic angle, $B_{lc}$ deg
- Rotor rotational speed, $\omega$ RPM
- Rotor shaft angle, $\alpha_s$ deg
- Blade flapping angle, $\beta$ deg
- Blade lag angle, $\zeta$ deg

(b) **Total Loads Balance and Instrumented Shaft**

- Axial force (thrust), $T$ lb
- Normal force, $NF$ lb
- Side force, $SF$ lb
- Pitching moment, $PM$ ft-lb
- Yawing moment, $YM$ ft-lb
- Shaft torque, $Q$ ft-lb

Forces and moments from the balances are printed on-line in engineering units as forces and moments with the wind-off zeros removed, with balance interaction corrections applied, and with the weight tares removed.

Corrected rotor balance forces and moments are reoriented into standard aircraft axes system and transferred on-line to the hub center so that moments could be evaluated in the plane of the rotor. The resolved shaft-axis system hub forces and moments are noted in the following list along with their sign convention.

**Rotor Hub Forces/Moments (Shaft Axes)**

- Thrust, $T$ (positive up) lb
- $H$ force (positive aft) lb
- Side force (positive to the right) lb
- Hub pitching moment (positive nose up) ft-lb
- Hub rolling moment (positive advancing tip down) ft-lb
- Yawing moment ($Q_f$, friction torque) ft-lb
Since the hub-generated forces and moments are included in the measured 'rotor' characteristics, it is necessary to establish hub tares and subtract them from the main rotor balance measurements. The hub tares are obtained from blade-off runs conducted at the normal operating speed. The rotor data is reduced on-line in coefficient form in the shaft axes system. Hub pitching moment, hub rolling moment and side force are retained in their more meaningful dimensional form.

Main rotor thrust coefficient, \( C_T/\sigma = \frac{T}{\rho (\Omega R)^2 A\sigma} \)

(Where \( \sigma \) is the rotor solidity)

Main rotor power coefficient, \( C_p/\sigma = \frac{Q}{\rho (\Omega R)^2 AR\sigma} \)

Rotor data is also reduced on-line in the following engineering units and non-dimensional forms in the wind axes system. Hub side force components are included when the model is yawed.

\[ D_e = \frac{\pi RPM}{30V} (Q-Q_f) - X \]

Lift to equivalent drag ratio, \( L/D_e \)

Rotor lift coefficient, \( C_rT/\sigma = \frac{L}{\rho (\Omega R)^2 A\sigma} \)

Propulsive force coefficient, \( \frac{X}{q\sigma^2} \) or \( \frac{X}{\bar{X}} \)

Figure 3.2 presents a sample printout.
<table>
<thead>
<tr>
<th>RUN</th>
<th>TP</th>
<th>M1</th>
<th>ALPHA</th>
<th>PNM</th>
<th>VTIP</th>
<th>P1(91°)</th>
<th>H(27°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>2</td>
<td>3.4990E-11</td>
<td>-1.7505E+11</td>
<td>7.08E+12</td>
<td>7.86E+12</td>
<td>1.24E+12</td>
<td>3.81E+12</td>
</tr>
</tbody>
</table>

**Figure 3.2 Sample Printout**

Sheet 3.5
4.0 TEST PROCEDURE AND CONDITIONS

4.1 Test Cell Checkout

4.1.1 Check on Tip Freedom of Movement

Before installing the rotor in the wind tunnel, the model was first checked for satisfactory operation and for freedom of movement of the tip. The check runs were made in the model test cell at gradually increasing tip speeds up to the normal operating speed of 700 ft/sec. At each speed a jet of compressed air was used to excite motion in the free tip and the response was observed. At low tip speed, the tip showed a highly damped response such as that presented in Figure 4.0a. At the operating tip speed no noticeable response was obtained; this is attributed to insufficient impulse being imparted by the air jets at the high tip speeds.

4.1.2 Determination of Controller Friction

Before actual wind tunnel testing was begun, a check was made of the friction forces acting on the pivot mechanism with simulated centripetal and lift loads applied to the tip. Various spanwise loads (to simulate $C_F$) were applied at the tip, co-linear with the main spar. The internal friction of the tip pivot mechanism was measured as a function of the resultant torque on the tip. The torque was measured using a simple cantilever beam attached to the tip, and a load cell attached between the end of the beam and ground.

Three separate types of loading were applied to the tip. A pure spanwise load applied in incremental units to simulate $C_F$ load, a combined load by applying a load in the spanwise direction at an angle to the main spar axis. A pure spanwise load was applied along with a load orthogonal to the main spar axis (to simulate a pure lift load). This final loading was performed to find the component of lift affecting the measurement of torque through the load-link. The test set-up is shown in Figure 4.0b.

Although there was some hysteresis present in the measurement, the test showed that the friction level was acceptable and slightly lower than the expected value.

The rotor and test stand was then removed from the test cell and installed in the Wind Tunnel. Each rotor tip configuration was tested using the following procedure.

4.2 Track and Balance

The rotor was run up to operating rpm and the blades tracked and
balanced. Balance was declared acceptable if the resultant in-plane force was less than 10 pounds.

4.3 Hover

Floor and ceiling were removed and rpm sweeps were made in hover, holding rotor thrust coefficient, $C_T$, constant. Following the rpm sweeps the rpm was set to give the required tip speed, and the collective varied from $-4^\circ$ in increments of $1^\circ$ up to the maximum achievable. This run was then repeated. In this way, excellent definition of the $C_p$ vs. $C_T$ curve was achieved. A high degree of definition is required in order to produce an adequate definition of rotor figure of merit.

4.4 Forward Flight

When the hover testing was complete the tunnel working section floor and ceiling were replaced ready for testing in forward flight. All testing was conducted with slotted floor, ceiling, and side walls.

At selected values of advance ratio (usually 0.2, 0.3, 0.35, 0.4) a thrust sweep at fixed shaft angle was made. Collective was increased until limited by power, cyclic control available, blade loads, or balance loads. The rotor was trimmed to give zero one-per-rev flapping.

Tip speed sweeps at fixed advance ratio ($\mu = .40$) were made by varying rpm while tunnel speed was adjusted to give the advance ratio. A constant value of $C_T$ and $X$ was maintained and the rotor trimmed to zero 1/rev flapping.

4.5 Hub Tares

In isolated rotor tests, the hubs, pitch arms, pitch housings, and attachments are not normally representative of the full scale rotor system and those differences must be accounted for aerodynamically. The contributions from the model blade pitch arms, housings, and hub were established by testing with the blades removed. The tests covered the entire range of advance ratios, shaft angles, and control settings likely to be used during the test. The values of the hub tares were then subtracted from the measured rotor forces to give the blades-only forces.

4.6 Run Log

A copy of the Wind Tunnel test engineer's Run Log is presented in Figure 4.1. The nomenclature and flag notes used in the Run Log are defined in Figures 4.2 and 4.3.
Figure 4.0a Response of Free-Tip to Air Jet in Hover

Sheet 4.3
Figure 4.0b Test Arrangement for Friction Pull Test
<table>
<thead>
<tr>
<th>RUN NO.</th>
<th>CONFIGURATION</th>
<th>TYPE OF RUN</th>
<th>WT. TARE RUN</th>
<th>m</th>
<th>g</th>
<th>RPM θ°</th>
<th>A,</th>
<th>C,</th>
<th>C²</th>
<th>α,°</th>
<th>DATE/TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>K₁</td>
<td>WARM UP</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>796</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4/20/61</td>
</tr>
<tr>
<td>3</td>
<td>✓</td>
<td>HUB TARE</td>
<td>✓</td>
<td>10</td>
<td>8</td>
<td>12</td>
<td>1.5</td>
<td>5.1</td>
<td></td>
<td></td>
<td>1837</td>
</tr>
<tr>
<td>5</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>1901</td>
</tr>
<tr>
<td>6</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>1941</td>
</tr>
<tr>
<td>7</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>1943</td>
</tr>
<tr>
<td>8</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>1944</td>
</tr>
<tr>
<td>9</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>1945</td>
</tr>
<tr>
<td>10</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>2015</td>
</tr>
<tr>
<td>11</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>2107</td>
</tr>
<tr>
<td>12</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>2108</td>
</tr>
</tbody>
</table>

**Figure 4.1 Test Run Log**

- **K**: Basic DRITs, Nose Paraging ON.
- **K₁**: HUB PA, PL, PL₁, F₁, F₂
- **WARM UP RUN**: Data after achieving 796 RPM.
- **DATA REJECTION**: Data double cut repeated as Run No. 5 (A = NG).
- **CYCLIC VALUES USED**: Variable values.
- **This Run On**: Values of cyclic are corrected (classical axes) values.
- **Control Variations**: @ W₅, Values of +1, -5, +1 (B, C, Then A, Then B₁).
<table>
<thead>
<tr>
<th>RUN NO.</th>
<th>CONFIGURATION</th>
<th>TYPE OF RUN</th>
<th>WT. TARE RUN</th>
<th>D'</th>
<th>RPM</th>
<th>E&lt;sub&gt;TE&lt;/sub&gt;</th>
<th>A</th>
<th>B</th>
<th>C&lt;sub&gt;1&lt;/sub&gt;</th>
<th>C&lt;sub&gt;F&lt;/sub&gt;</th>
<th>X</th>
<th>T/P ARMS</th>
<th>DATE / TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>$K_2 + V R I L 4 B 0 0 1 - \frac{\sigma}{2}$</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>4/23/61</td>
</tr>
<tr>
<td>14</td>
<td>$1 + B_1 B_2 B_3 B_4 W_6 W_7$</td>
<td>SEE WORKED</td>
<td>2</td>
<td>0</td>
<td>7%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>--</td>
<td>--</td>
<td>0.06</td>
<td>--</td>
</tr>
<tr>
<td>15</td>
<td>$1 + B_1 B_2 B_3 B_4 W_6 W_7$</td>
<td>--</td>
<td>-1</td>
<td>0</td>
<td>7%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>--</td>
<td>--</td>
<td>0.06</td>
<td>--</td>
</tr>
<tr>
<td>16</td>
<td>$1 + B_1 B_2 B_3 B_4 W_6 W_7$</td>
<td>--</td>
<td>-3</td>
<td>0</td>
<td>7%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>--</td>
<td>--</td>
<td>0.06</td>
<td>--</td>
</tr>
<tr>
<td>18</td>
<td>$1 + B_1 B_2 B_3 B_4 W_6 W_7$</td>
<td>--</td>
<td>-5</td>
<td>0</td>
<td>7%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>--</td>
<td>--</td>
<td>0.06</td>
<td>--</td>
</tr>
<tr>
<td>19</td>
<td>$1 + B_1 B_2 B_3 B_4 W_6 W_7$</td>
<td>--</td>
<td>-7</td>
<td>0</td>
<td>7%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>--</td>
<td>--</td>
<td>0.06</td>
<td>--</td>
</tr>
<tr>
<td>20</td>
<td>$1 + B_1 B_2 B_3 B_4 W_6 W_7$</td>
<td>--</td>
<td>-9</td>
<td>0</td>
<td>7%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>--</td>
<td>--</td>
<td>0.06</td>
<td>--</td>
</tr>
<tr>
<td>21</td>
<td>$1 + B_1 B_2 B_3 B_4 W_6 W_7$</td>
<td>--</td>
<td>-11</td>
<td>0</td>
<td>7%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>--</td>
<td>--</td>
<td>0.06</td>
<td>--</td>
</tr>
<tr>
<td>22</td>
<td>$1 + B_1 B_2 B_3 B_4 W_6 W_7$</td>
<td>--</td>
<td>-13</td>
<td>0</td>
<td>7%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>--</td>
<td>--</td>
<td>0.06</td>
<td>--</td>
</tr>
<tr>
<td>23</td>
<td>$1 + B_1 B_2 B_3 B_4 W_6 W_7$</td>
<td>--</td>
<td>-15</td>
<td>0</td>
<td>7%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>--</td>
<td>--</td>
<td>0.06</td>
<td>--</td>
</tr>
</tbody>
</table>

**DRTS - CONTRAST LIFT TIP:**
- EVANT

**FREE TIP:**
- Evant

---

**Figure 4.1 Test Run Log - Continued**
<table>
<thead>
<tr>
<th>RUN NO.</th>
<th>CONFIGURATION</th>
<th>TYPE OF RUN</th>
<th>WT. TARE RUN</th>
<th>M'</th>
<th>RPM</th>
<th>C1</th>
<th>A1</th>
<th>B1</th>
<th>\Delta</th>
<th>C1/\theta</th>
<th>T/P</th>
<th>DATE / TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>K + VER 61 B001 - 1 + B2, B3, B4, W2</td>
<td>FF 18&quot;</td>
<td>.35</td>
<td>79%</td>
<td>FOR</td>
<td>FOR</td>
<td>T1</td>
<td>T1</td>
<td>D</td>
<td>1/15</td>
<td>9%</td>
<td>4/23 0601</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Y 10 DATA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 4.1 Test Run Log - Continued**
<table>
<thead>
<tr>
<th>RUN NO.</th>
<th>CONFIGURATION</th>
<th>TYPE OF RUN</th>
<th>WT. TARE RUN</th>
<th>$\mu$</th>
<th>RPM</th>
<th>$\beta_{75}$</th>
<th>$A_1$</th>
<th>$B_1$</th>
<th>$\alpha_s$</th>
<th>$C_{10}$</th>
<th>$\lambda$</th>
<th>TIP ASY</th>
<th>DATE / TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>$k_2$ + VEIGH B004-1 $B_2^0$ $18^0 17^0$ W1</td>
<td>PF Flight Test</td>
<td>18</td>
<td>0.35</td>
<td>79°C</td>
<td>For C/2</td>
<td>For Trim</td>
<td>For Angling</td>
<td>10</td>
<td></td>
<td></td>
<td>4/11/61</td>
<td>2052 2215</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td>0.30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td>0.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td></td>
<td></td>
<td></td>
<td>0.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>42</td>
<td></td>
<td></td>
<td></td>
<td>0.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>43</td>
<td></td>
<td></td>
<td></td>
<td>0.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44</td>
<td></td>
<td></td>
<td></td>
<td>0.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td></td>
<td></td>
<td></td>
<td>0.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46</td>
<td></td>
<td></td>
<td></td>
<td>0.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.1 Test Run Log - Continued
<table>
<thead>
<tr>
<th>RUN NO.</th>
<th>CONFIGURATION</th>
<th>TYPE OF RUN</th>
<th>WT. TARE RUN</th>
<th>μ</th>
<th>RPM</th>
<th>θ_2</th>
<th>A_1</th>
<th>B_1</th>
<th>α_1</th>
<th>C_{T/L}</th>
<th>X</th>
<th>TIP ASSY</th>
<th>DATE / TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>K_2 (VR 161 B001-1) B_4</td>
<td>FF</td>
<td>18</td>
<td>35</td>
<td>796</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>48</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>49</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

49. AX WEIGHTS IN TLP
Flag Note Summary

1. $\alpha_s = -20^\circ$ to $+10^\circ$ by $3^\circ$
2. $\theta_{75} = 14.5^\circ \pm 4^\circ$
3. $A_1 = 3.5^\circ \pm 2^\circ$
4. $B_{1C} = 6.2^\circ \pm 2^\circ$
5. $C_{T'}/\sigma = .04, .06, .08, .09 \rightarrow$ Max by .01's (Power Limit)
6. Not Used
7. Not Used
8. $c_s = 0^\circ, -1^\circ, -3^\circ, -4^\circ$
9. $\alpha_s^0 = -12, -9, -5, -2, +2, +4, +6, +7, \alpha_s$ for autorotation
10. $\alpha_s^0 = -5, -7, -9, -12, -2$
11. $\alpha_s^0 = -6^\circ, \pm 2, \pm 4$ about trim, controls fixed
12. $\mu' = .35, .325, .375, .3375, .3625$
13. $\alpha_s = -5^\circ, -9^\circ, -11$
14. Not Used
15. Not Used
16. $C_{T'}/\sigma = 0 \rightarrow$ Max by .01 (Power Limit)
17. RPM = 400 $\rightarrow$ 850 by 50
18. $\alpha_s = 2, -5, -9$

Figure 4.2 Flag Note Summary
Component Descriptions

$K_1$ = Basic D.R.T.S. - Nose Fairing On
   - 75:1 Gear Box
   - Upper Stack Fairing

$B_X$ = Blade Number X

$W_0$ = Extra light weight

$W_1$ = Light weight tip

$W_2$ = Mid weight tip

$W_3$ = No weights in tip

Figure 4.3 Component Descriptions
5.0 TEST RESULTS AND ANALYSIS

The complete test data on the performance and vibratory loads of the free tip rotor are presented in detail in Appendix A. This section summarizes the main results of the test and presents a simple analysis which is used to explain some of the trends observed in the results.

5.1 Analysis

The analysis is based on the following simplifying assumptions:

1. Quasi-steady aerodynamics
2. Uniform downwash
3. Inelastic blade
4. Inviscid flow

With reference to Figure 5-1, let s be the chordwise coordinate, r the blade radial coordinate, t the local thickness, \( \Omega \) the rotor rotational speed, \( \theta \) the flapping angle, and \( \phi \) the pitch angle of the free tip at azimuth \( \psi \). An element of mass located at \( r, s, t \) within the tip contributes to the pivot moment an amount

\[
\frac{dm}{dt} = \sigma ds \, dr \, ds \, dt
\]

then the inertial moment about the pivot is

\[
M_{cf} = \frac{1}{2} \rho^2 \left[ I \sin^2 \beta \cos \theta - I_p \sin 2\theta \right]
\]

where \( I_p \) is the pitch inertia about the pivot and \( I \) is the product of inertia of the tip about the pivot line and the blade flapping axis.

The centrifugal force has a component in the direction of positive flapping,

\[
Z_{cf} = -\frac{1}{2} \rho^2 M_{fp} \sin 2\beta
\]

where \( M_{fp} \) is the mass moment of the tip about the flapping pin.

In summary, the contributions from centrifugal force are a moment, \( M_{cf} \), about the pivot and a force, \( Z_{cf} \), normal to the blade acting through the pivot.
Referring to Figure 5-1, let \( Z_a \) be the aerodynamic force normal to the free tip, acting at the quarter chord, \( M_k \) be the aerodynamic moment acting about the quarter chord line, \( M_F \) be the total moment exerted by the pivot on the tip, and \( R_{FY} \) the force exerted by the pivot on the tip.

Resolving in the direction of positive flapping,

\[
Z_a + Z_{af} - F_{pivot} - W \cos \beta = \frac{W}{g} \left[ R_{q\beta} + (S_p - S_0) \ddot{\theta} \right]
\]

and taking moments about the tip center of mass,

\[
Z_a (S_p - S_0) + (R_{am} - Z_{af})(S_p - S_0) + M_{ka} + M_k + M_{cf} = I_G \ddot{\phi}
\]

Combining these eliminates the pivot reaction and yields

\[
Z_a (S_p - S_0) - W(S_p - S_0) \cos \beta + M_{ka} + M_k + M_{cf} = \frac{W}{g} (S_p - S_0) \left[ R_{q\beta} + (S_p - S_0) \ddot{\theta} \right] + I_F \ddot{\phi}
\]

For the c.g. lying on the pivot, \( S_p = S_0 \) and the pitch equation of motion reduces to

\[
Z_a (S_p - S_0) + M_{ka} + M_k + M_{cf} = I_G \ddot{\phi}
\]

i.e., the tip motion is inertially uncoupled from the flapping motion of the blade.

Expressing the forces in terms of the blade motion

\[
Z_a = \frac{1}{2} \rho V_r^2 (x + \mu \sin \psi)^2 C_{L_3} x S
\]

\[
M_{ka} = \frac{1}{2} \rho V_r^2 (x + \mu \sin \psi)^2 r S^2 \left[ \frac{\partial C_{mf} + C_{mo}}{\partial c} \right]
\]

\[
M_{cf} = - I_p \ddot{\theta}
\]

where

\( C_{L_3} \) is the free tip lift-curve slope

\( C_{mo} \) is the quarter-chord pitching moment coefficient at zero lift

\( x \) is the mean radial distance of the free tip
Figure 5.1 Notation

Sheet 5.3
\( \alpha \) is the tip angle of attack
and \( \varepsilon \) is the tip reference area

Putting \( \ell = s_p - c/4 \), the pitch equation of motion becomes

\[
\ddot{\theta} + \theta = \left[ \frac{\frac{1}{2} \rho V_t^2 c \varepsilon (C_{\alpha} + \frac{1}{2} C_{\alpha}^2)}{I_c} \right] \alpha (x + \mu \sin \psi)^2
+ \frac{1}{2} \beta \frac{V_t^2 c \varepsilon}{I_c} C_{\alpha} (x + \mu \sin \psi)^2 + \frac{M_{\psi}}{(I_c c)^2}
\]

where \( \beta = \frac{20}{2 \psi^2} \)

Assuming a uniform downwash velocity \( v_i \), the blade angle of attack is

\[
\alpha = \theta - \frac{\overline{v_i} + x \overline{\beta} - \mu \sin \alpha s}{x + \mu \sin \psi}
\]

where \( \overline{v_i} = v_i / V_t \) and \( \overline{\beta} = \frac{d \beta}{d \psi} \)

If the blade tip pitch motion is

\[
\theta = \theta_0 - \sum_{n=1}^{\infty} \theta_{ns} \sin n \psi - \sum_{n=1}^{\infty} \theta_{nc} \cos n \psi
\]

and if the first harmonic flapping motion is given by

\[
\beta = a_0 - a_1 \cos \psi - b_1 \sin \psi
\]

then by substitution in the equation of motion, and retaining only the first two harmonics of the pitching motion, the following set of equations is obtained for the blade pitch angle coefficients:

\[
\begin{bmatrix}
\theta_0 \\
\theta_{1s} \\
\theta_{1c} \\
\theta_{ss} \\
\theta_{sc}
\end{bmatrix}
= \begin{bmatrix}
A_{1s} \\
A_{1c} \\
A_{ss} \\
A_{sc}
\end{bmatrix}
\]
Writing

\begin{align*}
P &= \frac{1}{2} \rho \frac{V_t^2 C_{\mu}}{I_g \Omega^2} \left[ 1 + \frac{\partial C_{\mu}}{\partial C_L} \right] \\
Q &= \frac{1}{2} \rho \frac{V_t^2 C_s}{I_g \Omega^2} \\
8 &= \frac{M_F}{(I_g \Omega^2)} \\
\gamma &= x^2 + \frac{1}{2} \mu^2
\end{align*}

the coefficients \( a_{ij}, A_j \) are given in Figure 5-2.

In hover, \( \mu = 0 \) and \( \gamma = x^2 \), and the solution yields

\begin{align*}
\theta_{2c} &= 0 = \theta_{2c} \\
\theta_{1s} &= -a_i \\
\theta_{1c} &= b_i \\
\text{and } \theta_0 &= \left[ 8 + \alpha x^2 - P_x K \sqrt{C_T} \right] / (1 - P_x^2),
\end{align*}

since \( \bar{V}_i = k' \sqrt{C_T} \frac{\sqrt{C_T}}{2(1-x^2)} = k \sqrt{C_T} \).

The interesting feature of this result is that in hover pitching motion of the free tip follows the flapping motion of the main blade and, further, if cyclic pitch is applied to the main blade, i.e.,

\begin{align*}
\theta_M &= \theta_{15} - A_{1c} \cos \psi - B_{1c} \sin \psi \\
&= \theta_{15} - b_{1c} \cos \psi + a_{1c} \sin \psi \quad \text{(in hover)}
\end{align*}

then the angle of the free tip relative to the main blade is

\[ \delta = \theta_{1f} - \theta_M \]

where \( \Delta \) is the twist between the tip of the main blade and \( x = 0.75 \).
\[
\begin{array}{ccccccc}
\theta_0 & \theta_3 & \theta_c & \theta_s & \theta_{2s} & \theta_{2c} \\
\frac{-1}{4}P \mu^3 & -P \mu x & -P \mu x & \frac{p^2 \mu x}{2} & \frac{p^2 \mu x}{2} & \frac{p^2 \mu x}{2} & A_i \\
0 & 0 & 0 & 3 + P \mu x & 0 & 0 & A_{ij} \\
-P \mu x & P \mu x & 0 & 0 & 0 & 0 & A_{ij} \\
1 - P \mu x & P \mu x & 0 & 0 & 0 & 0 & 0 \\
\end{array}
\]

Figure 5.2 Coefficients $a_{ij}$, $A_i$.
which is constant for a given thrust condition. Thus, the analysis shows that angle of the free tip with respect to the main blade will not change when cyclic pitch is applied in hover. This behavior was observed during the hover testing.

The nose-up moment exerted by the pivot on the free tip is proportional to the centripetal force acting on the tip and can be shown to be given by (see Figure 5.3)

\[
M_f = -\frac{\pi \rho L^2 R_x}{3} \left[ \frac{\tan \delta - \bar{\mu} \sin(\delta)}{1 + \bar{\mu} \tan \delta \sin(\delta)} \right]
\]

where \(d_1, d_0\) are the outer and inner diameters of the helical contact surface between the follower pin and the guide,

\(\alpha\) is the helical screw angle,

\(\bar{\mu}\) is the coefficient of friction between pin and guide,

and \(\delta\) is the pitch rate of the free tip.

5.2 Test Results

As stated earlier, the complete test data is presented in Appendix A. Only the main points are discussed here.

5.2.1 Hover Performance

Hover performance was measured with the tip free at the light weight condition. No data was taken with the tip fixed, so a direct assessment of the effect of the free tip on hover performance cannot be made. An indirect assessment was obtained, however, using theory. Figure 5.4 shows the measured variation of power with thrust, Figure 5.5 shows the corresponding figure of merit and Figure 5.6 shows the angle of the free tip relative to the main blade. Theoretical calculations of hover performance were made using Boeing computer program B92 by treating the free tip angle as a step change in blade twist. The predictions of rotor power coefficient corresponding to the measured tip angles and thrust coefficients are shown on Figure 5.4 and the figure of merit on Figure 5.5.

Agreement between measured and predicted performance is good and shows that the tip angle was measured correctly. Also shown on these figures is the predicted performance for the tip fixed (\(\delta = 0\)). A general reduction in hover performance is predicted
Figure 5.3 Pivot Screw Geometry

Sheet 5.8
Figure 5.5 Variation of Figure of Merit with Thrust Coefficient with Tip-Free and Comparison with Theory
Figure 5.6 Variation of the Tip Angle, $\delta$, and Comparison with Analysis
for the rotor with the tip free. At $C_T/\sigma = 0.088$, the reduction in figure of merit is estimated to be 7%.

Figure 5.6 shows the variation of the steady tip angle with rotor thrust coefficient. Also shown is the prediction of the simple analysis described above. In making the calculations, the variation of the tip lift-curve slope and aerodynamic center position with aspect ratio given in Figures 5.7 and 5.8 was used.

5.2.2 Forward Flight Performance

5.2.2.1 Effect of Free Tip on Power Required

Results from the forward flight testing show that, for the same propulsive force and lift, the rotor requires more power with the tip free than with it locked. The data of Figure 5.9 is typical. The plot shows the variation of power with advance ratio at $C_T'/\sigma = 0.06$ and $\bar{x} = 0.05$ with the tip free at mid weight and with the tip fixed. At $\mu = 0.4$, the increase in power required is 23% and at $\mu = 0.3$ it is 27%. The corresponding lift-to-effective drag ratios are shown in Figure 5.10. The collective pitch settings are plotted in Figure 5.11, which shows that approximately 0.5° less collective is required with the tip free.

5.2.2.2 Effect of Thrust Level on Tip Response

The azimuthal variation of the free tip angle with changes in rotor lift is presented in Figures 5.12 through 5.16. The data was obtained at $\mu = 0.3$ for the mid weight tip. The fact that propulsive force varies from case to case does not substantially change the general trends observed. The free tip angle, $\delta$, is the angle of the tip measured relative to the inboard main blade. The angle of the tip relative to the disc plane (i.e., the local blade angle, $\theta_{\text{Tip}}$) was calculated knowing $\delta$ and the collective and cyclic inputs. Both $\delta$ and $\theta_{\text{Tip}}$ are presented in the figures.

From the plots, it can be seen that the maximum variation of the relative tip angle $\delta$ over the azimuth is about 0.3 degrees for $C_T/\sigma = 0.0409$. As the thrust is increased, the average value of $\delta$ falls and more variation occurs around the azimuth until at $C_T'/\sigma = 0.12144$ fluctuations of 0.8 degrees occurs in the fourth quadrant of the disc. In terms of the tip blade angle, $\theta_{\text{Tip}}$, at low $C_T/\sigma$ the minimum value is approximately 10 degrees and occurs at $\psi = 150^\circ$. The maximum value is 14.5° occurring at 330° azimuth. As thrust is increased, the minimum value of $\theta_{\text{Tip}}$ increases slightly to 11 degrees at $C_T/\sigma = 0.12144$ but the maximum value rises to 25 degrees at 310° azimuth. The large blade tip angles encountered on the first and fourth quadrants suggest that the tip is in a stalled condition which would be consistent with the increased power observed.
Figure 5.7 Variation of Lift-Curve Slope with Aspect Ratio

(from Reference 3)
Figure 5.8 Variation of Aerodynamic Center with Aspect Ratio
(From Reference 3)
Figure 5.9 Comparison of Power Required, Tip Fixed and Free
Figure 5.10  Comparison of Rotor Lift-to-Effective Drag Ratio, Tip Fixed and Free
Figure 5.11 Comparison of Main Blade Collective Pitch, Tip Fixed and Free
Figure 5.12 Tip Response at \( \mu = .30, \frac{C_T}{\sigma} = .0409 \)
Figure 5.13 Tip Response at $\mu = .30$, $C_T'/\sigma = .0612$
Figure 5.14 Tip Response at $u = .30$, $C_T' / \sigma = .0843$
\( \frac{C_T}{\sigma} = 0.1113 \)

\( \bar{X} = 0.007689 \)

\( A_1 = -4.9796 \)

\( B_1 = 3.6512 \)

\( \theta = 9.1444 \)

\( \theta_{\text{TIP}} = 0.75 - A_1 \cos \psi - B_1 \sin \psi + \delta - 2.25 \)

Figure 5.15 Tip Response \( \mu = 0.30, \frac{C_T}{\sigma} = 0.1113 \)
Figure 5.16  Tip Response at $\mu = 0.30$, $C_T'/\sigma = 0.12144$
5.2.2.3 Effect of Tip Weight on Tip Response

The effect of tip weight and inertia on tip response is summarized in Figure 5.17, which shows the azimuthal variation of relative tip angle $\delta$ for the tip with mid weight, light weight, extra light weight and no tip weights added. For all cases the rotor lift is the same and approximately the same propulsive force is being produced. As the tip becomes lighter, the nose-up moment produced by the screw controller decreases and hence it would be expected that tip equilibrium would be reached at progressively lower tip angles. This is, in fact, what is observed and tends to confirm that the tip was operating freely.

Another expectation is that tip response would be increased at reduced tip inertia and weight. Again this is in accord with the measured tip behavior, as can be seen from Figure 5.17.

5.2.3 Vibratory Hub Loads

Throughout the test, hub vibratory forces and moments were measured. The 4/rev resultant in-plane and out-of-plane vibratory hub loads are plotted in Appendix A. It should be noted that these vibratory loads are uncorrected for any dynamic amplification that may have been present in the rotor test stand and hub. The data should not, therefore, be used as absolute quantities, though they may be used to make comparisons between tip configurations.

A typical finding of the test concerning vibratory hub loads is shown in Figures 5.18 and 5.19. Figure 5.18 compares the 4/rev vertical hub force with the tip fixed and free. With the tip free, the hub loads are about double those measured with the tip fixed. Figure 5.19 presents the corresponding resultant 4/rev in-plane force. In this instance, the free tip reduces the in-plane loads by 45% at $u = 0.3$ and by 16% at $u = 0.4$.

5.3 Discussion

The test results show that with the tip free, rotor performance was reduced in both hover and forward flight. The measured tip angle in hover (Figure 5.6) revealed that the tip was deflected nose-up by as much as 14° relative to the main blade. This introduces an effective positive tip twist to the rotor which is in the opposite direction to that needed to improve hover performance. As shown by the comparison with theory (Figures 5.4 and 5.5), the reduced hover performance is caused by the unfavorable twist.

The free tip was designed, and the pivot location selected at 13% chord so that the tip would operate at a $C_L = 1.15$ on the retreating side of the rotor disc at $u = 0.35$. A value for the tip lift-curve slope of 5.73 per radian was used and the aerodynamic
Figure 5.17 Effect of Tip Weights on Tip Response
Figure 5.18 Comparison of Vertical Vibratory Hub Loads, Tip Fixed and Free
Figure 5.19 Comparison of the Inplane Vibratory Hub Loads, Tip Fixed and Free

Sheet 5.26
center was assumed to lie on the quarter chord line. Based on these conditions, an effective angle of attack at the blade tip of 4° would be expected in hover at 681 ft/sec tip speed. If the downwash velocity at the rotor is assumed to be given by the momentum result

\[ \frac{V_t}{V_i} = k \sqrt{\frac{C_T}{2}} \]

and the collective by

\[ \theta_{25} = k \sqrt{\frac{C_T}{2}} + \frac{6C_T}{\sigma a} \]

then the expected variation of tip angle with rotor thrust coefficient would be as shown in Figure 5.6. The calculated levels are considerably less than those measured.

The main reason for the discrepancy between the expected and actual tip angles is that the tip lift-curve slope was over-estimated. The use of 5.73/rad for the overall lift-curve slope implies that the tip is part of a very high aspect ratio wing with a uniform lift distribution. This overlooks the drop-off in lift distribution at the blade tip and does not address the tendency of the tip to behave as a low aspect ratio surface, as illustrated in Figure 5.20. It would be expected, therefore, that the tip lift-curve slope would fall considerably below the two-dimensional value used in the design, and that the aerodynamic center position would move away from the quarter-chord point toward the leading edge. The variation of lift-curve slope and aerodynamic center position with aspect ratio is shown in Figures 5.7 and 5.8 and is taken from Reference 3. The combination of these effects would tend to increase the tip angle to the levels observed. With the tip operating at high angles of attack, the induced and profile drag would be greatly increased, resulting in much greater power requirements.

The tendency for the tip to operate at high angles could have been reduced by lowering the moment applied by the controller. However, no means was available for adjusting the controller moment. This would be a desirable feature in future designs.

In summary, the results of the test indicate that the free tip was operating at angles of attack well beyond those intended in the design. This is attributed to the lowered lift-curve slope and forward movement of the aerodynamic center on the low aspect ratio tip. The high angles of attack gave rise to high tip drag and reduced performance.
Figure 5.20 Development of Low Aspect Ratio Flow at Free Tip

Sheet 5.28
6.0 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

A wind tunnel test of a 16.8 ft. diameter free tip rotor was conducted in hover and in forward flight up to an advance ratio of 0.4. Based on the test results and analysis, the following conclusions are drawn:

1. The measured operating angle of the free tip was much greater than that anticipated during the design phase. This is the primary cause of the performance degradation.

2. Model hover performance was reduced when operating the rotor with the tip free, compared to that with the tip fixed.

3. The model power required in forward flight with the tip free was greater than that measured with the tip fixed at all advance ratios tested, when both rotors are operating at the same lift and propulsive force.

4. The large operating angle of the free tip is attributed to low aspect-ratio tip effects which reduce the tip lift effectiveness, increase the tip induced drag and move the aerodynamic center forward. The magnitude of these effects was not fully known when the tip was designed.

5. Hub 4/rev vertical loads were increased when the tips were free compared to the tip-fixed loads measured at the same operating condition.

6. Hub 4/rev in-plane loads were reduced with the tip free compared to the tip-fixed loads measured at the same operating condition.

Recommendations

Research should be directed toward understanding the complex, low aspect ratio flow conditions existing on the free tip. When these low aspect ratio tip aerodynamics are understood, this knowledge can be used to design a free tip rotor that will demonstrate the full potential of the concept. This research effort is best approached by a combination of analytical modeling and wind tunnel testing. Specifically, it is recommended that:

1. A wind tunnel test should be conducted using nonrotating, semispan models of the free tip. The test would gather data on the tip lift, drag, and pitching moment characteristics over the full operating Mach number range at combinations of main blade and free tip angles of attack. Various tip spans would also be tested to measure the effect of tip aspect ratio on the aerodynamic characteristics.
2. In parallel with the wind tunnel test, a detailed analytical model of a free tip rotor should be developed with attention being focused on representing the low aspect ratio tip effects. The model would make extensive use of the data obtained from the wind tunnel test.

3. When the analytical model is completed and verified, it should be used to design a free tip rotor that will provide improved performance and reduced vibratory loads.

4. An alternate means should be explored for providing the tip controlling moment.
7.0 REFERENCES


APPENDIX A. TEST DATA

Presented in this Appendix are the basic data plots for all the free tip rotor configurations tested. The data is corrected for hub tares. No corrections were applied for wall effects because the test was conducted with the working-section slots open, a configuration that yields essentially free-air conditions. The rotor advance ratios and free-tip configurations tested, together with the page number where the data is presented, are shown in the table below.

<table>
<thead>
<tr>
<th>μ</th>
<th>FIXED, LIGHT WEIGHT</th>
<th>FREE, MID WEIGHT</th>
<th>FREE, LIGHT WEIGHT</th>
<th>FREE, EXTRA LIGHT WEIGHT</th>
<th>FREE, NO WEIGHTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>-</td>
<td>A-4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>.20</td>
<td>-</td>
<td>A-45</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>.30</td>
<td>A-11</td>
<td>A-56</td>
<td>A-89</td>
<td>A-111</td>
<td>A-144</td>
</tr>
<tr>
<td>.35</td>
<td>A-21</td>
<td>A-67</td>
<td>A-100</td>
<td>A-122</td>
<td>A-155</td>
</tr>
<tr>
<td>.40</td>
<td>A-31</td>
<td>A-78</td>
<td>-</td>
<td>A-133</td>
<td>A-166</td>
</tr>
</tbody>
</table>

The terms light weight, mid weight, etc., refer to the number and arrangement of the tip weights. These are shown in Table A-1.

The data plots are presented in the following order:

Hover

$C_T/\sigma$ vs. $C_p/\sigma$

$PM$ vs. $C_T/\sigma$

$\beta, 75$ vs. $C_T/\sigma$

$\delta$ vs. $C_T/\sigma$

$C_p/\sigma$ vs. $M_{1,90}$

$C_T/\sigma$ vs. $M_{1,90}$

$\delta$ vs. $M_{1,90}$
<table>
<thead>
<tr>
<th>CONDITION</th>
<th>TIP INERTIA ABOUT PIVOT (SLUG FT²)</th>
<th>TIP WEIGHT (LB)</th>
<th>ARRANGEMENT OF WEIGHTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MID WEIGHT</td>
<td>3.88 x 10⁻⁵</td>
<td>0.501</td>
<td><img src="image" alt="Arrangement" /></td>
</tr>
<tr>
<td>LIGHT WEIGHT</td>
<td>3.24 x 10⁻⁵</td>
<td>0.341</td>
<td></td>
</tr>
<tr>
<td>EXTRA LIGHT</td>
<td>2.5 x 10⁻⁵</td>
<td>0.255</td>
<td></td>
</tr>
<tr>
<td>NO WEIGHTS</td>
<td>1.758 x 10⁻⁵</td>
<td>0.169</td>
<td></td>
</tr>
</tbody>
</table>

Table A-1 Tip Configuration, Weights, and Inertias
Forward Flight

*Cp/\sigma vs. M_{1.90}

*CT'/\sigma vs. M_{1.90}

*L/DE vs. M_{1.90}

*Resultant 4/rev Inplane Moment vs. M_{1.90}

CT'/\sigma vs. Cp/\sigma

L/DE vs. CT'/\sigma

\bar{X} vs. CT'/\sigma

A_{1C} vs. CT'/\sigma

B_{1C} vs. CT'/\sigma

\delta_{.75} vs. CT'/\sigma

**\delta vs. CT'/\sigma

Resultant 4/rev Hub Vertical Force vs. CT'/\sigma

Resultant 4/rev Hub Inplane Force vs. CT'/\sigma

Alternating Blade Torsion at x = .13 vs. CT'/\sigma

Resultant 4/rev Inplane Moment vs. CT'/\sigma

*Presented only for tip fixed, light weight, \nu = .4

**Not presented for tip fixed, since \delta = 0

The definitions of the quantities presented in the plots are given on the following page.
LIST OF SYMBOLS FOR APPENDIX A

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Rotor disc area, $\pi R^2$, ft$^2$</td>
</tr>
<tr>
<td>$A_{1C}$</td>
<td>Lateral cyclic pitch, degrees</td>
</tr>
<tr>
<td>B</td>
<td>Number of blades</td>
</tr>
<tr>
<td>$B_{1C}$</td>
<td>Longitudinal cyclic pitch, degrees</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Rotor power coefficient, $550 \frac{\text{RHP}}{\rho AV_T^3}$</td>
</tr>
<tr>
<td>$C'T$</td>
<td>Rotor lift coefficient, $L/\rho AV_T^2$</td>
</tr>
<tr>
<td>c</td>
<td>Blade chord, ft.</td>
</tr>
<tr>
<td>D</td>
<td>Rotor diameter, ft.</td>
</tr>
<tr>
<td>$D_E$</td>
<td>Rotor effective drag, $550 \frac{\text{RHP}}{V} - X$, lb</td>
</tr>
<tr>
<td>FM</td>
<td>Rotor figure of merit, $.707C'T^3/2/C_p$</td>
</tr>
<tr>
<td>L</td>
<td>Rotor lift, lb</td>
</tr>
<tr>
<td>$M_{1.90}$</td>
<td>Advancing blade tip Mach number</td>
</tr>
<tr>
<td>q</td>
<td>Free stream dynamic pressure, $\frac{1}{2}\rho V^2$</td>
</tr>
<tr>
<td>R</td>
<td>Blade radius, ft.</td>
</tr>
<tr>
<td>RHP</td>
<td>Rotor shaft horsepower</td>
</tr>
<tr>
<td>V</td>
<td>Tunnel speed, fps</td>
</tr>
<tr>
<td>$V_T$</td>
<td>Rotor tip speed, fps</td>
</tr>
<tr>
<td>X</td>
<td>Rotor propulsive force, lb</td>
</tr>
<tr>
<td>$\bar{X}$</td>
<td>Rotor propulsive force coefficient, $X/qD^2\sigma$</td>
</tr>
<tr>
<td>$\alpha_s$</td>
<td>Rotor shaft angle, positive aft. degrees</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Angle of free tip relative to main blade (positive nose)</td>
</tr>
<tr>
<td>$\theta_{.75}$</td>
<td>Blade collective pitch at .75R, degrees</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Rotor advance ratio, $V/V_T$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Air density slug/ft$^3$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Rotor solidity, $Bc/\pi R$</td>
</tr>
</tbody>
</table>
NASA-BOEING FREE-TIP ROTOR
BYVT 271
MU' = 0 TIP FREE LIGHT WT.  CT/σ = 0.07

STEADY TIP ANGLE

ADVANCING BLADE TIP MACH NUMBER M1 (DB)

RUN 45005
\( \frac{C_T}{\alpha} = 0.07 \)

\( \bar{x} = 0.05 \)
NASA-BOEING FREE-TIP ROTOR
BUWT 271
MU* = .40 TIP FIXED LIGHT UT.

COLLECTIVE
THETA = 2.5

ROTOR LIFT COEFFICIENT CT' / \theta

RUN 39 O -2
RUN 39A O -5
RUN 39B O -9
RUN 39C O -11
WASA-BOEING FREE-TIP ROTOR
BUWT 271
MU'=.40 TIP FIXED LIGHT UT.

RESULTANT 4/REU INPLANE FORCE

ROTOR LIFT COEFFICIENT CT'/SIGMA

RUN 39  o
RUN 39A  o
RUN 39B  o
RUN 39C  o

N5
-5
-7
-11
ORIGINAL FAX IS OF POOR QUALITY
NASA-BOEING FREE-TIP ROTOR
MU' = .30 TIP FREE LIGHT UT.

RESULTANT 4-REU INPLANE FORCE

ROTOR LIFT COEFFICIENT C'T'/SIGMA
ORIGINAL PAGE IS
OF POOR QUALITY
NASA-BOEING FREE-TIP ROTOR
Bw. 271
MU = .35 TIP FREE LIGHT WT.

LATERAL CYCLIC A1-CORR

ROTOL LIFT COEFFICIENT CT'/SIGMA

RUN 33 O -5
RUN 33A © -7
RUN 34 O -2
RUN 34A © -5
RUN 34B A -7
RUN 34C © -9
RUN 34D P -12
NASA-BOEING FREE-TIP ROTOR
SYST 271
PIU's .48 TIP FREE EXTRA LIGHT VT.

COLLECTIVE

THETA

-9

-5

-2

ROTOR LIFT COEFFICIENT CT/SIGMA

RUN 60 O -9
RUN 83A □ -5
RUN 83B ◆ -9
APPENDIX B. DATA CROSS PLOTS

Using the basic test data presented in Appendix A, extensive cross plots against advance ratio were made for the mid weight condition with the tip fixed and with it free. This data is presented for the following range of $C'T/\sigma$ and $\overline{X}$.

<table>
<thead>
<tr>
<th>$\overline{X}$</th>
<th>$C'T/\sigma$</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>0.08</td>
<td>B-1a</td>
</tr>
<tr>
<td>0.10</td>
<td>0.06</td>
<td>B-10</td>
</tr>
<tr>
<td>0.10</td>
<td>0.04</td>
<td>B-19</td>
</tr>
<tr>
<td>0.05</td>
<td>0.08</td>
<td>B-28</td>
</tr>
<tr>
<td>0.05</td>
<td>0.06</td>
<td>B-37</td>
</tr>
<tr>
<td>0.05</td>
<td>0.04</td>
<td>B-46</td>
</tr>
<tr>
<td>0</td>
<td>0.08</td>
<td>B-55</td>
</tr>
<tr>
<td>0</td>
<td>0.06</td>
<td>B-64</td>
</tr>
<tr>
<td>0</td>
<td>0.04</td>
<td>B-73</td>
</tr>
</tbody>
</table>

At each $\overline{X}$ and $C'T$ the order of the plots is

- $C_p/\sigma$ vs. $\mu'$
- $L/D_F$ vs. $\mu'$
- $\alpha_s$ vs. $\mu'$
- $\theta_{75}$ vs. $\mu'$
- $A_1$ vs. $\mu'$
- $B_1$ vs. $\mu'$
- $\delta$ vs. $\mu'$

4/rev resultant vertical force vs. $\mu'$
4/rev resultant inplane force vs. $\mu'$
Event 271 Constant Lift Tip

△ Tip Free Mid Weight
△ Tip Fixed

\( \frac{C_L}{\sigma} = 0.08 \)
\( \frac{X}{d_0^2} \sigma = 0.01 \)

Original data is of poor quality

Rate Lift To Effective Drug Ratio, \( \lambda \)

Advance Ratio, \( \mu \)
Event 271 Constant Lift Tip

- Tip Free Midweight
- Tip Fixed

$C_l/6 = .08$
$K/9D^2_6 = .10$

Advance Ratio, $\mu^*$
BUNJ 271 CONSTANT LIFT TIP

- TIP FREE MID WEIGHT
- TIP FIXED

\[
\frac{C_l}{a} = 0.08 \\
\frac{\lambda}{c^2/4} = 0.10
\]
BUNT 271  CONSTANT LIFT TIP
L. TIP FREE MID WEIGHT
D. TIP FIXED
C/\alpha = 0.08
X/\rho D^2 = 0.10

ADVANCE RATIO, \( \mu \)

\begin{align*}
&\text{Cone Angle, } A_1, \text{ Deg.} \\
&\text{Lifting Cycle, } A_1, \text{ Deg.}
\end{align*}

\begin{align*}
&\text{Fixed} \\
&\text{Free}
\end{align*}
BVWT 271 Constant Lift Tip

- ▲ Tip Free Mid Weight
- ▲ Tip Fixed

\[ \frac{C_l}{S} = 0.08 \]
\[ \frac{x}{0.026} = 0.10 \]

B-6
\[ \Delta \text{ Tip Free and Weight} \]
\[ \text{(Tip Fixed \( \delta = 0 \))} \]

\[ C/10 = 0.08 \]
\[ x/D = 0.10 \]
Event 271 Constant Lift Tip

- Tip Free M:O Weight
- Tip Fixed

$C_{T/0} = 0.08$

$X/9D^20 = 0.10$

Resultant Vertical Force

Advance Ratio, $\mu$

B-8

KMD 10/9/81
BUWT 271 Constant Lift Tip

△ Tip Free and Weight
△ Tip Fixed

CT/G = .08
X2/D2 = .10
ORIGINAL PAGE IS OF POOR QUALITY

BUNIT 271 CONSTANT LIFT TIP

\[ \frac{C_t}{S} = 0.06 \]

\[ \frac{x}{9D^2} = 0.10 \]

Rotor Power Coefficient, \( C_p/\mu \)

Advance Ratio, \( \mu \)

B-10

KMD 10/3/81
BWT 271 CONSTANT LIFT TIP

- TIP FREE, MILD WEIGHT
- TIP FIXED

\[ C_l/C = 0.06 \]
\[ x/\rho D = 0.10 \]

![Graph showing lift to advance ratio relationship](image-url)

B-11
ORIGINAL PAGE IS OF POOR QUALITY

\[ \text{BUILT \ JI \ CONSTANT \ LIFT \ TIP} \]

- Tip Free Mid Weight
- Tip Fixed

\[ \frac{C}{S} = 0.06 \]
\[ \frac{x}{D} \psi = 0.10 \]

\[ \text{Advance Ratio, } \mu \]

\[ \text{Shaft Angle, } \alpha_y \]

\[ \begin{array}{c}
\text{Fixed} \\
\text{Free}
\end{array} \]
BVT 271 CONSTANT LIFT TIP

- Tip Free Mid Weight
- Tip Fixed

\[
\frac{C_f}{a} = 0.06
\]
\[
x/LD^2 = 0.10
\]

Collective, \( \beta \)

Advance Ratio, \( \mu' \)
EYWT 271 CONSTANT LIFT TIP
- Tip Free Mid Weight
- Tip Fixed

\[ \frac{C}{C} = 0.06 \]
\[ \frac{V}{gD^2C} = 0.10 \]

Advance Ratio, \(\mu^\prime\)

Current Circum, M - cos2
BUNT 271 CONSTANT LIFT TIP

- Tip free midweight
  (Tip fixed \( \delta = 0 \))

\[
\frac{C_I}{C} = 0.06 \\
\frac{x}{\theta_{20}} = 0.10
\]

![Graph showing lift ratio vs. advance ratio](image)
Event 271  Constant Lift Tip

- Tip Free Mid Weight
- Tip Fixed

$C_{t/i} = .06$

$X/g_{o}^2 \rho \cos \theta = 10$

Advance Ratio, $\mu'$

$\mu'$ vs. Resultant Vertical Force
BUNT 371 CONSTANT LIFT TIP

- Tip Free and Weight
- Tip Fixed

\[ C_{\text{L}}/C = 0.06 \]
\[ \times 1/9D^2 = 0.10 \]
ORIGINAL PAGE IS OF POOR QUALITY

**EVT T-271 CONSTANT LIFT TIP**

- **TIP FREE MID WEIGHT**
- **TIP FIXED**

\[ \frac{C_l}{C} = 0.04 \]
\[ \frac{x}{D} \mu = 0.10 \]

**Force Power Coefficient, \( \frac{S}{P} \)**

**Advance Ratio, \( \mu' \)**

B-19

REv. 10/5/81
ORIGINAL PAGE IS OF POOR QUALITY

But if constant lift tip

- Tip free mid weight
- Tip fixed

\[ \frac{C_l}{C} = 0.01 \]
\[ \frac{x}{2D^2} C = 0.10 \]

Graph showing lift curve with lift curves for free and fixed tips.
BUWIT 271 CONSTANT LIFT TIP

○ TIP FREE MID WEIGHT

• TIP FIXED

\[ C_{L/0} = 0.04 \]

\[ X/9D^2C = 0.10 \]

ADVANCE RATIO \( \mu \)

---

Diagram showing the relationship between shaft angle and advance ratio with points labeled Free and Fixed.
ORIGINAL PHOTO IS OF POOR QUALITY

BUWT 271 CONSTANT LIFT TIP

○ TIP FREE MID WEIGHT
● TIP FIXED

\[ C_l/C = 0.04 \]
\[ N/D^2 C = 0.10 \]

Diagram:

- Collection: B.75
- Advance Ratio, \( \mu' \)

B-22

KMG 10/5/81
B&W T-271 CONSTANT LIFT TIP

○ TIP FREE M/D WEIGHT

● TIP FIXED

\[ C_{L}/C = 0.04 \]
\[ X/D^2 C = 0.10 \]

ADVANCE RATIO, \( \mu \)

\[ H_{L\text{FREE}} - C_{L\text{FREE}} \]

\[ H_{L\text{FIXED}} - C_{L\text{FIXED}} \]
CONSTANT LIFT TIP

○ TIP FREE MHD WEIGHT
● TIP FIXED

\[
\frac{c}{D} = 0.04 \\
x/D^2 = 0.10
\]

Graph showing the relationship between advance ratio, \( \mu \), and lift parameter.
BWR 271 CONSTANT LIFT TIP

- TIP FREE MID WEIGHT
  (TIP FIXED \( \delta = 0 \))

\[ C_{t/\alpha} = .06 \]
\[ x/q \hat{D}^2 \alpha = .10 \]
Blunt 27/ Constant Lift Tip

○ Tip Free M/D Weight
● Tip Fixed

\[ C_{l} / C_s = 0.24 \]
\[ x / g D^2 \alpha = 0.10 \]
GUNT 271  CONSTANT LIFT TIP

○ TIP FREE MID WEIGHT
● TIP FIXED

\[ C_{T/\Delta} = 0.04 \]
\[ x/bD^2 \Delta = 0.10 \]
Event 271 Constant Lift Tip

- Tip Free Mid Weight
- Tip Fixed

\[ \frac{C_l}{c} = 0.08 \]

\[ \frac{x}{D_{20}} = 0.05 \]

Graph: Force Lift-To-Effective Drag Ratio vs \( \mu' \)

Parameters: \( C_l/c \), \( x/D_{20} \)

Legend:
- Fixed
- Free

Advance Ratio, \( \mu' \)

Axes:
- \( y \) axis: Force Lift-To-Effective Drag Ratio
- \( x \) axis: Advance Ratio, \( \mu' \)
CUNT 271 CONSTANT LIFT TIP

△ TIP FREE WICE WEIGHT
△ TIP FIXED

$C_l/g = 0.08$
$\frac{X/90^2}{g} = 0.05$

ADVANCE RATIO, $\mu$

Advance Ratio, $\mu$

ADVANCE RATIO, $\mu$

SMART ANGLE, $\delta$

SMART ANGLE, $\delta$

SMART ANGLE, $\delta$

SMART ANGLE, $\delta$
ORIGINAL PAGE IS
OF POOR QUALITY

\[ \frac{C_l}{C} = 0.08 \]
\[ \frac{x}{0.2C} = 0.05 \]

\( \Delta \) Tip Free Mid Weight
\( \Delta \) Tip Fixed

\( C_l/C \)

Advance Ratio, \( \mu \)

Collective, \( \theta \)
Blunt 27.1 Constant Lift Tip

Tip Free and Weight
Tip Fixed

$C_l/6 = 0.08$

$X/8D^2/6 = 0.05$

Advance Ratio, $\mu$

Diagram showing the relationship between advance ratio and lift cycle.
BVWT Z71 CONSTANT LIFT TIP

△ TIP FREE MILD WEIGHT
△ TIP FIXED

$C_{T}/C = 0.08$
$x/qD^2C = 0.05$

LONGITUDINAL CYCLE $C_{L}$ - CORR

ADVANCE RATIO, $u'$

B-33

KMB: 10/01/81
Event 271: Constant Lift Tip

- Tip Free Mid Weight
  (Tip Fixed $\delta = 0$)

- $C_l/c = 0.08$
- $x/\rho D^2 C = 0.5$

**Graph:**
- Axes: Advance Ratio, $\mu'$ vs Tip Angle, $\delta$
- Data points indicating lift behavior for different advance ratios.
CONSTANT LIFT TIP

△ TIP FREE MIO WEIGHT
○ TIP FIXED

\[ \frac{C_t}{\delta} = 0.08 \]
\[ \frac{X}{qD^2} = 0.05 \]

ADVANCE RATIO, \( \mu \)

FREE

FIXED

A/GV RESULTANT THRUSTING FORCE

200
160
120
80
40
0
0
0.1
0.2
0.3
0.4
0.5

B-26

KMs 10/3/61
ORICINAL FACE IS
OF POOR QUALITY

BVNT 271 CONSTANT LIFT TIP

- TIP FREE MID WEIGHT
- TIP FIXED

\[ \frac{C_l}{S} = 0.06 \]
\[ \frac{V}{2\pi D} \rho = 0.05 \]

Advance Ratio, \( \mu' \)

Kerrie Lift to Effective Disc Ratio, \( \mu' \)
BVT 271  CONSTANT LIFT TIP

- TIP FREE AND WEIGHT
- TIP FIXED

\[ \frac{C_l}{\alpha} = 0.06 \]
\[ \frac{x}{\theta D}^2C = 0.05 \]
BUNIT 271 Constant Lift Tip

- Tip Free M.W.
- Tip Fixed

$C_l/\alpha = 0.06$
$X/gD^2 = 0.05$

Advance Ratio, $\mu$
 Eternal 271 Constant Lift Tip

- Tip Free Midweight
- Tip Fixed

$C_l/g = 0.06$

$X/gD^2 = 0.05$

![Graph showing lift coefficient (C_l) vs advance ratio (μ') with data points labeled 'Fixed' and 'Free'.]
TIP FREE MID WEIGHT
(TIP FIXED \( \delta = 0 \))

\[ C_{T/\alpha} = 0.06 \]
\[ C_{S} = 0.05 \]
BVMT Z71  Constant Lift Tip

C_t/I = 0.04
x/2D = 0.05

Advance Ratio, \( \mu \)
Event 27: Constant Lift Tip

- Tip Free
- Tip Fixed

\[ C_l/d = 0.04 \]
\[ x/d^2 c = 0.05 \]

Graph: Force Lift to Effective Drag Ratio, \( \mu' \) vs Advance Ratio, \( \mu' \)
ORIGINAL PAGE IS OF POOR QUALITY

**EVT 271** CONSTANT LIFT TIP

- **TIP FREE MID WEIGHT**
- **TIP FIXED**

\[ C_l/C = 0.06 \]
\[ x/\rho L^2 C = 0.05 \]

**ADVANCE RATIO, \( \mu' \)**

![Graph](image)

**CHUTE ANGLE, \( \alpha \)**
BWI-271 Constant Lift Tip

- Tip Free Mid Weight
- Tip Fixed

\[ \text{C}_{10} = 0.04 \]
\[ \text{x}/\text{D}_2\text{C} = 0.05 \]

![Graph showing collective vs advance ratio for free and fixed tips.](image-url)
Evwt 271 Constant Lift Tip

- Tip Free Mid Weight
- Tip Fixed

\[ \frac{C_T}{\sigma} = 0.04 \]
\[ \frac{x}{D^2} D = 0.05 \]

Advance Ratio, \( \mu' \)

Diagram showing lateral cyclic motion with labeled lines for fixed and free conditions.
B&WTV 271 Constant Lift Tip

- Tip Free Mid Weight
- Tip Fixed

\[ \frac{C_f}{6} = 0.04 \]
\[ x/80^{26} = 0.05 \]
BWT 271 Constant Lift Tip

○ Tip Free and Weight (Tip Fixed \( \delta = 0 \))

\[ C_l/\sigma = 0.04 \]
\[ x/gD^2 \sigma = 0.05 \]
BWT 271 CONSTANT LIFT TIP

- Tip Free Mid Weight
- Tip Fixed

$C_l/C = 0.04$
$X/qD^2C = 0.05$

Graph showing A/REV Resultant Vertical Force against Advance Ratio, $\mu'$.
Rotor Power Coefficient, \( C_p/\sigma \)

- **Advance Ratio, \( \mu \):**
  - 0.3
  - 0.5
  - 0.8
  - 1.0
  - 1.2

- **Tip Free Mid Weight:**
  - \( 0 = 0.25 \text{ ft} \)
  - \( 8.0 = 0.15 \text{ ft} \)

- **Fixed:**
  - \( 0 = 0.8 \text{ ft} \)
  - \( 8.0 = 0.15 \text{ ft} \)

- **Swept:**
  - \( 0 = 0.25 \text{ ft} \)
  - \( 8.0 = 0.15 \text{ ft} \)

- **L-35**

- **1991-1996**

- **Original Page 13 of Poor Quality**
BWT 271  Constant Lift Tip

△ Tip Free and Mid Weight
△ Tip Fixed

\[ \frac{C_l}{c} = 0.08 \]
\[ \frac{x}{D^2} \Delta = 0 \]

Force Lift-To: Effective Drag Ratio, \( \frac{C_l}{c} \)

Advance Ratio, \( \mu \)

B-56  XMB 10/6/81
Original face is of poor quality.

BVWT 271 Constant Lift Tip

Δ Tip Free Mid Weight
Δ Tip Fixed

$q/\sigma = 0.08$

$x/\theta_0^2 \sigma = 0$

Collective, roll

Advance Ratio, $\mu$

Fixed
Free

B-58

KMIB 10/6/81
ORIGINAL PAGE IS OF POOR QUALITY

BYWT 271 CONSTANT LIFT TIP

- Tip free
- Tip fixed

\[ C_l/\sigma = 0.08 \]
\[ x/g^2 \sigma = 0 \]

Advance ratio, \( \mu \)

Lateral cyclic, A - Core

\( \mu \)

B-59

KMB 10/8/81
**EVWT 271 Constant Lift Tip**

- △ Tip Free Mid Weight
- ▲ Tip Fixed

\[ \frac{C_l}{C} = 0.08 \]
\[ \frac{x}{\text{b}^2} \text{C} = 0 \]

---

**Graph:**

- **Y-axis:** Coning Angle, \( \alpha \)
- **X-axis:** Advance Ratio, \( \mu \)

- **Lines:**
  - **Fixed**
  - **Free**

---

**Legend:**

- **B-60**
- **KINZ 10/8/81**
\( \Delta \) Tip Free Mid Weight
(Tip Fixed \( \delta = 0 \))

\[
\frac{C_l}{c} = 0.08
\]

\[
x/cD^2 = 0
\]
ORIGINAL FACE IS OF POOR QUALITY

BUWT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT
△ TIP FIXED

\[
\frac{C_l}{C_l} = 0.08 \\
x/\delta z = 0
\]

\[\text{ADVANCE RATIO, } \mu\]

\[\text{4/REV RESULTANT INPLANE FORCE}\]

\[0 \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5\]

\[0 \quad 40 \quad 60 \quad 120 \quad 160 \quad 200\]
EVNT 271 CONSTANT LIFT TIP

\[
\frac{C_l}{C} = 0.06
\]

\[
\frac{X}{gD^2} = 0
\]

\[\text{Roller Power Coefficient, } \frac{S}{I}\]

\[\text{Advance Ratio, } \mu\]

\[\begin{array}{c}
\text{FREE} \\
\text{FIXED}
\end{array}\]

\[\text{TIP FREE MEDIUM WEIGHT} \\
\text{TIP FIXED}\]
BUWU 271 CONSTANT LIFT TIP

- Tip Free Mid Weight
- Tip Fixed

\[ \frac{C_l}{C} = 0.06 \]
\[ \frac{x}{qD^2C} = 0 \]
Bullet 271: Constant Lift Tip

- Tip Free and Mid Weight
- Tip Fixed

\[ \frac{C_l}{C} = 0.06 \]
\[ x/D = 0 \]

Advance Ratio, \( \mu' \)

**Diagram:**
- "Free" line
- "Fixed" line

Sweep Angle, \( \alpha_s \)

- Scale: 0 to 20

B-66
TIP FREE MID WEIGHT
TIP FIXED

\[ \frac{C_{T}}{C} = 0.06 \]
\[ \frac{X}{gD^2} = 0 \]

ADVANCE RATIO, \( \mu' \)

LATERAL CYCLIC, \( A_{1} \)-CORE

\[ \begin{array}{c}
0.5 \\
0.4 \\
0.3 \\
0.2 \\
0.1 \\
0.0 \\
-0.1 \\
-0.2 \\
-0.3 \\
-0.4 \\
-0.5 \\
-0.6 \\
-0.7 \\
-0.8 \\
-0.9 \\
-1.0 \\
\end{array} \]
EVENT 271  CONSTANT LIFT TIP

- TIP FREE MID WEIGHT
- TIP FIXED

\[ \frac{C_l}{C} = 0.06 \]
\[ \frac{x}{8D^2} = 0 \]
BUNT 271 CONSTANT LIFT TIP

TIP FREE MID WEIGHT
(TIP FIXED δ = 0)

\[ \frac{C_l}{C} = 0.06 \]
\[ \frac{r}{b} \delta^2 \delta = 0 \]

Tip Angle, \( \delta \)

Advance Ratio, \( \mu \)
EVT W 271 CONSTANT LIFT TIP

- Tip Free Mid Weight
- Tip Fixed

$C_{\tau}/\sigma = 0.06$

$x/B^2 = 0$

Graph showing the relationship between advance ratio and resultant vertical force.
D'TT 271 CONSTANT LIFT TIP

- Tip Free and Weight
- Tip Fixed

\[ C_{T/0} = 0.6 \]
\[ \frac{X}{2D^2} = 0 \]

---

B-72
CIVILIAN FACE IS
OF POOR QUALITY

BUWT 271 CONSTANT LIFT TIP

○ TIP FREE M ID WEIGHT
■ TIP FIXED

\[
\frac{C_t}{C} = 0.04 \\
\frac{x}{D} = 0
\]
Rotor Lift-to-Effective Drag Ratio, $L/D_e$
BVWT 271 CONSTANT LIFT TIP

○ TIP FREE MID WEIGHT
● TIP FIXED

\[ C_{T/\sigma} = 0.04 \]
\[ x/\rho D^2 \sigma = 0 \]

ADVANCE RATIO, \( \mu \)

SHAFT ANGLE, \( \alpha_s \)

FREE

FIXED

B-75

KMB 10/8/61
Buvt 271 Constant Lift Tip

- Tip Free Mid Weight
- Tip Fixed

\[ \frac{C_l}{S} = 0.04 \]
\[ \frac{X}{gD^2c} = 0 \]

Graph showing the relationship between Collective (θ) and Advance Ratio (μ).

B-76

KMB 10/8/81
LATERAL CYCLIC, $A_{-}\text{corr}$

Advance Ratio $\frac{a}{c}$

BUNT 271

- Tip Free
- Tip Fixed

Advance Ratio $\frac{a}{c}$

$\frac{a}{c} = 0.4$

$X_{1,2,3} = 0$

Original pace is of poor quality.
Blunt 271 Constant L/C Tip

○ Tip Free Mid Weight
● Tip Fixed

\[
\frac{C_{T/0}}{C_0} = 0.04 \\
x/D_0 = 0
\]
BVWT 271 CONSTANT LIFT TIP

- **Tip Free Mid Weight**
  
  \( \frac{C_l}{\delta} = 0.04 \)
  
  \( \frac{x}{\delta D^2} \delta = 0 \)

**Diagram**: Graph showing the relationship between advance ratio and tip angle. The graph has labels and data points indicating different conditions or cases. The axis labels are not explicitly mentioned in the text but are inferred from the context of the diagram.