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DYNAMIC RESPONSE OF THE OV-1A AIRCRAFT TO SOFT FIELD LANDINGS

By

William T. Alexander

October 1971

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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DISPOSITION INSTRUCTIONS

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This report describes part of a continuing project directed toward the establishment of aircraft design criteria for rough-terrain landing operations.

The report presents the ground loads measured on an instrumented OV-1 airplane during landings on smooth and rough fields. Test results for three landings are compared with the results of dynamic loads computations performed on a digital computer.

The computing program is also used to calculate the loads which would have been obtained by landings and rollouts on the roughest portions of two fields whose contours were measured, as part of this project. Failing loads were obtained on one field only.

The equations of motion for the computer program are presented in an appendix. Recommendations are made for future investigations that will improve the analytical procedures.
### KEY WORDS

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<th>Aircraft</th>
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<th>Rough Terrain</th>
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DYNAMIC RESPONSE
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Final Report

By

William T. Alexander

EUSTIS DIRECTORATE
U.S. ARMY AIR MOBILITY
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ABSTRACT

A U.S. Army OV-1A Mohawk aircraft was instrumented to measure the loads and attendant stresses incurred during landing and taxiing on unprepared (sod) fields typical of Army operations. Reported herein are the test results and analytical correlation of three landings, one of which resulted in failure of the nose gear and strike damage to the aircraft.

The field effort described is an extension to an earlier investigation conducted in 1964 at the Landing Loads Test Track Facility, Langley Field, Virginia, in which a single OV-1A main gear was subjected to simulated landings. The basis for these investigations has been the refinement of a computerized mathematical model for landing gear developed by the McDonnell-Douglas Aircraft Company of Long Beach, California, which can be used in the establishment of design criteria for aircraft whose mission requires operations in and out of unprepared areas. Results of these efforts have established that the landing gear loads induced by ground roughness can be quite severe and could result in undesirable restrictions and attrition if not properly recognized in the aircraft design.
FOREWORD

The program reported in this document was conducted under the Department of the Army Research and Development Task 1F162204A14602, Rough Terrain Landing Loads. The program was conducted by the Aeromechanics Division of the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory. The field tests reported herein were performed during July and August 1967 at Franklin, Virginia.

Acknowledgement is made of the contributions of the Douglas Aircraft Company, Long Beach, California, who instrumented the three landing gear, performed the analytical correlation with the actual field tests, and prepared the reports on these two phases of effort. Special recognition is extended to Mr. Fred Allen, who directed these efforts under Contract DA 44-177-AMC-404(T) with the U.S. Army Air Mobility Research and Development Laboratory. Recognition is given the personnel of the Engineering and Technical Services Division who endured many wintry days measuring the profile roughness of several prospective test sites; designed, calibrated, and installed the total instrumentation system with the exception of the landing gear; and processed and reduced the oscillographic records for analysis. Also, Mr. Duane Simon, the OV-1 pilot, is acknowledged for his cooperation and exposure in such a hazardous operation.
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<tr>
<td>A</td>
<td>planform area of rut formed during horizontal movement $\Delta X$, in.$^2$</td>
</tr>
<tr>
<td>D</td>
<td>drag load (resistance to forward motion imposed on aircraft by soil), lb</td>
</tr>
<tr>
<td>D</td>
<td>drag load on gear (normal to strut), lb</td>
</tr>
<tr>
<td>$D_B$</td>
<td>drag load which exists at full tire deflection, lb</td>
</tr>
<tr>
<td>DL</td>
<td>drag load, left main gear, lb</td>
</tr>
<tr>
<td>DR</td>
<td>drag load, right main gear, lb</td>
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<tr>
<td>$E_A$</td>
<td>horizontal kinetic energy subtracted from airplane resulting from application of force $D$, lb-in.</td>
</tr>
<tr>
<td>$E_S$</td>
<td>energy imparted to soil as a result of soil deformation, lb-in.</td>
</tr>
<tr>
<td>F</td>
<td>force, lb</td>
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<tr>
<td>$K_1,..,K_n$</td>
<td>proportionality constants</td>
</tr>
<tr>
<td>$p$</td>
<td>footprint pressure of tire on ground, psi</td>
</tr>
<tr>
<td>$p_o$</td>
<td>tire inflation pressure, psi</td>
</tr>
<tr>
<td>$P_T$</td>
<td>force exerted by ground on tire, lb</td>
</tr>
<tr>
<td>$P_{TB}$</td>
<td>force on tire at full tire deflection, lb</td>
</tr>
<tr>
<td>$P_T(FAILURE)$</td>
<td>force on tire when soil fails, lb</td>
</tr>
<tr>
<td>S</td>
<td>strut stroke from fully extended position, in.</td>
</tr>
<tr>
<td>S</td>
<td>side load, lb</td>
</tr>
<tr>
<td>SL</td>
<td>side load, left gear, lb</td>
</tr>
<tr>
<td>SR</td>
<td>side load, right gear, lb</td>
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V  vertical load (parallel to strut axis), lb
VL  vertical load, left gear, lb
VR  vertical load, right gear, lb
w  tire width, in.
X  horizontal distance in direction of airplane motion, in.
δ  deflection of oscillograph trace obtained during a test run, in.
δ_S  soil deformation, in.
δ_SB  soil deformation under load P_{TB}, in.
Δ  deflection of oscillograph trace during calibration run, in.
μ  coefficient of friction
μ_{R}  rolling coefficient of friction
μ_S  sliding coefficient of friction

SUBSCRIPTS
A  aft
D  drag
F  forward
S  side
V  vertical

NOTE:  Symbols used in computer program are given in Tables VIII through XIII and in Appendix I.
INTRODUCTION

This report presents the actual measured responses of the OV-1A landing gear and airframe when performing landings on an unprepared soil strip. These data are then compared to analytical findings based on the roughness measured for the particular landing site. Although the program was planned for several landings on a minimum of three different fields, it could not be completed because of the test aircraft crash on the first landing attempt. The study, therefore, had to be limited to the crash landing and two practice landings made prior to the crash.

The report is divided into three sections plus appendixes. Section I, "Instrumentation Report", describes the procedures used in instrumenting, calibrating, and deriving the load equations for the landing gear. Section II, "Field Tests", describes the field measurements and total aircraft instrumentation. Section III, "Computed Loads and Comparison With Test Results", presents the method used in calculating the dynamic loads, discusses correlation of the analytical and measured results, and gives conclusions and results of the findings. The appendixes contain the equations of motions and forces used for the analytical effort and other supporting documents pertinent to the program.
SECTION I. INSTRUMENTATION REPORT

CALIBRATION PROCEDURE FOR STRAIN GAGE LOCATIONS

Stress-cote data and photographs of strain gage locations on the Grumman AO-1 main gear lower piston were used to locate the bonded resistance strain gages on the two main gears of the YOV-1 airplane (Figure 1). The axle area contains twelve strain gages in groups of three oriented in 45-degree rosettes with the center gage parallel with the center line of the axle. Gages were located from stress-cote patterns that indicate a minimum interaction response for a given direction of loading. Rosette gages were located at theoretical positions of maximum shear and maximum bending. All gages on the main gears were connected as one quarter active gages so that individual strain responses could be recorded at every gage location. A typical bridge circuit is illustrated in Figure 2. Gage installation and locations are outlined on Douglas drawing Z7890978.

Strain gages were located on the nose gear axle at the planes of maximum bending moment and configured to provide a four-active-arm bridge that minimizes interactions from loads applied in directions other than the principal direction. Two full bridges for vertical load and two full bridges for drag load were installed. The axle installation is shown in Figure 3.

Selection of Strain Gage Combinations for Main Gears

The two main gears were individually loaded to various single-direction and combined-direction loads. The responses from all of the strain gages were recorded as punch card data and entered with a special computing program. The program selects full or partial bridge channels from various strain gage combinations such that a given channel will give a maximum response to a given load condition. Interaction responses on any channel were considered at a minimum when they were less than 5 percent of the maximized values.

The vertical, drag, and side load channels were identified as LV-1, LV-2, LV-3, LD-1, LD-2, LD-3, LS-1, LS-2 for the left main gear and RV-1, RV-2, RV-3, RD-1, RD-2, RD-3, RS-1, RS-2 for the right main gear. A sample channel wiring diagram is shown in Figure 4. The left main gear miniature cannon connector pin and gage lead are identified in Figure 5.
Static Calibration

The gears were individually loaded again in a static test jig to various single-load and combined-load conditions. A static calibration photograph appears in Figure 6. The responses from each strain gage channel were recorded. These values and input load values were introduced into a second computer program that provided sets of equations for each combination of vertical, drag, and side channels. Eighteen sets of equations were obtained from the eight channels of strain gages. Equations are shown in Tables I and II. Equations for the nose gear were calculated for vertical and drag directions for four strain gage bridges. Four sets of equations are shown in Table III.

Dynamic Calibration

The main landing gears were serviced and instrumented as shown in Figure 7. The transducers were mounted and set up to measure strut position; lower mass vertical, drag, and side accelerations; upper mass vertical acceleration; wheel rpm; and oil and air pressure. Strain gages, transducers, and vertical load and drag load from the reaction platform were recorded on oscillographs during a succession of drops ranging from 6 feet to 27 feet. The data obtained were analyzed and the final gage combinations that were to be read during flight test were selected. A typical drop record is shown in Figure 8.

The nose gear was serviced in the prescribed manner, placed in the drop test jig, and dropped in a succession of drops. Instrumentation recorded during these drops included vertical and drag accelerations, vertical and drag strain gage channels, and vertical and drag reaction platform channels. The data obtained were recorded on oscillographs and analyzed. Figure 9 shows the nose gear drop test setup.

Equations derived from the static calibration were reviewed by applying data from the drop tests. Those bridge combinations showing the best correlation between static calibrations and drop tests were selected as primary and spare combinations to be recorded in the flight test program. The bridge numbers and combinations for the left main gear in order of preference are LV-2, LD-2, LS-2; LV-1, LD-2, LS-2; LV-2, LD-1, LS-2; and LV-2, LD-2, LS-1. The bridge numbers and combinations for the right gear are RV-1, RD-1, RS-1; RV-3, RD-1, RS-1; RV-1, RD-2, RS-1; and RV-1, RD-1, RS-2. The bridge numbers and combinations for the nose gear are NV-1, ND-1; NV-1, ND-2; NV-2, ND-1; and NV-2, ND-2. Load channel curves and final equations are discussed on pages 12 through 15.
INSTRUMENTATION RÉSUMÉ

Strain Gages

Installation - DAC Drawing Z7890978

Calibration equations for main gears are shown in Tables I and II. Calibration equations for nose gear are shown in Table III. Best sets are listed in Table VI.

Air Pressure Transducers

Installation - Shown in Figure 10 for right main gear.

Type - CEC 4-313 Pressure Pickup

Serial No. - Left Main Gear - 21222
             Right Main Gear - 20750

Calibration - [shunt type across (+) input and (+) output]
             LMG: 100KΩ = 1054 psi
             RMG: 100KΩ = 1024 psi

Accelerometers

Installation - DAC Sketch #41417, Drawings Z7892350 and Z7892245

Types - Lower Vertical and Drag, All Gears
             Statham A6-100-350 Accelerometer
             Upper Vertical and Lower Side Main Gears
             Statham A5-50-350 Accelerometer

Serial No. - Lower Vertical LMG - 11455, I-10979
             Lower Vertical RMG - 11459, I-10982
             Lower Vertical NG - 11458, I-10981
             Lower Drag LMG - 11454, I-10978
             Lower Drag RMG - 11153, I-10977
             Lower Drag NG - 11452, I-10976
             Lower Side LMG - 13774, I-10984
             Lower Side RMG - 13771, I-10987
             Upper Vertical LMG - 13776, I-10986
             Upper Vertical RMG - 13775, I-10985
Calibration - \[100K\Omega\text{ shunt across (+) input and (+) output}\]

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<th>Value</th>
<th>Direction</th>
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<td>Lower Vertical LMG</td>
<td>20.23</td>
<td>(+ Down)</td>
</tr>
<tr>
<td>Lower Vertical RMG</td>
<td>20.82</td>
<td>(+ Down)</td>
</tr>
<tr>
<td>Lower Vertical NG</td>
<td>19.58</td>
<td>(+ Down)</td>
</tr>
<tr>
<td>Lower Drag LMG</td>
<td>21.15</td>
<td>(+ Aft)</td>
</tr>
<tr>
<td>Lower Drag RMG</td>
<td>20.12</td>
<td>(+ Aft)</td>
</tr>
<tr>
<td>Lower Drag NG</td>
<td>20.14</td>
<td>(+ Aft)</td>
</tr>
<tr>
<td>Lower Side LMG</td>
<td>11.19</td>
<td>(+ Outboard)</td>
</tr>
<tr>
<td>Lower Side RMG</td>
<td>10.81</td>
<td>(+ Outboard)</td>
</tr>
<tr>
<td>Upper Vertical LMG</td>
<td>10.74</td>
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</tr>
<tr>
<td>Upper Vertical RMG</td>
<td>10.22</td>
<td>(+ Down)</td>
</tr>
</tbody>
</table>

**Oil Pressure Transducers**

Installation - DAC Sketch #22888

Type - CEC 4-313 Pressure Pickup

Serial No. - Left Main Gear - 21638
Right Main Gear - 22118

Calibration - \[100K\Omega\text{ shunt across (+) input and (+) output}\]

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMG</td>
<td>1064</td>
<td>psi</td>
</tr>
<tr>
<td>RMG</td>
<td>996</td>
<td>psi</td>
</tr>
</tbody>
</table>

**RPM Transducer**

Installation - Drawing Z7892245

Type - Electro #3055 Magnetic Pickup

Output - Varies depending on distance from pip plate (1 pip/rev)

**Strut Deflection (Stroke)**

Installation - Drawing Z7892350

Type - Douglas Design Z7892350

Identification - LMG - DI #1
RMG - DI #2
NG - DI #3
Calibration - [100KΩ shunt across (+) input and (+) output] (Figure 11)
DI #1 - 44.8 deg = 100K
DI #2 - 45.9 deg = 100K
DI #3 - 44.9 deg = 100K

<table>
<thead>
<tr>
<th>Channel Combinations</th>
<th>VR</th>
<th>DR</th>
<th>SR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K₁</td>
<td>K₂</td>
<td>K₃</td>
</tr>
<tr>
<td>1 1 1</td>
<td>16135</td>
<td>-669</td>
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<tr>
<td>1 1 2</td>
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</tr>
<tr>
<td>3 3 2</td>
<td>-38136</td>
<td>-431</td>
<td>-1522</td>
</tr>
</tbody>
</table>

Load Equations Based Upon: V - Cal @ 100K-Ohms; D - Cal @ 100K-Ohms; S - Cal @ 100K-Ohms; \( \Delta V \) = Ratio Run/Cal Pip for Gage V; \( \Delta D \) = Ratio Run/Cal Pip for Gage D; \( \Delta S \) = Ratio Run/Cal Pip for Gage S.

VR = \( K₁ \frac{\Delta V}{\Delta} + K₂ \frac{\Delta D}{\Delta} + K₃ \frac{\Delta S}{\Delta} \)

DR = \( K₄ \frac{\Delta V}{\Delta} + K₅ \frac{\Delta D}{\Delta} + K₆ \frac{\Delta S}{\Delta} \)

SR = \( K₇ \frac{\Delta V}{\Delta} + K₈ \frac{\Delta D}{\Delta} + K₉ \frac{\Delta S}{\Delta} \)
<table>
<thead>
<tr>
<th>Channel Combinations</th>
<th>VL</th>
<th>DL</th>
<th>SL</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV</td>
<td>LD</td>
<td>LS</td>
<td>K₁</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>13490</td>
</tr>
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<td>2</td>
<td>14112</td>
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<td>13854</td>
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<td>1</td>
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<td>3</td>
<td>2</td>
<td>14362</td>
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<td>2</td>
<td>1</td>
<td>1</td>
<td>16480</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>16331</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>15643</td>
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<td>2</td>
<td>2</td>
<td>15681</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>1</td>
<td>16945</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
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<td>16203</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>24809</td>
</tr>
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<td>3</td>
<td>1</td>
<td>2</td>
<td>25869</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1</td>
<td>26015</td>
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<td>3</td>
<td>2</td>
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<td>27151</td>
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<td>3</td>
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<td>25522</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2</td>
<td>26812</td>
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</tbody>
</table>

Load Equations Based Upon: V = Cal @ 100K-Ohms; D = Cal @ 100K-Ohms; S = Cal @ 100K-Ohms; \((\delta/\Delta)_{V}\) = Ratio Run/Cal Pip for Gage V; \((\delta/\Delta)_{D}\) = Ratio Run/Cal Pip for Gage D; \((\delta/\Delta)_{S}\) = Ratio Run/Cal Pip for Gage S; VL = Vert Load on Wheel lb; DL = Drag Load on Wheel lb + Aft; SL = Side Load on Wheel lb + Outb’d.

VL = \(K_{1}(\Delta_{V}) + K_{2}(\Delta_{D}) + K_{3}(\Delta_{S})\)

DL = \(K_{4}(\Delta_{V}) + K_{5}(\Delta_{D}) + K_{6}(\Delta_{S})\)

SL = \(K_{7}(\Delta_{V}) + K_{8}(\Delta_{D}) + K_{9}(\Delta_{S})\)
<table>
<thead>
<tr>
<th>TABLE III. EQUATIONS FOR YOV-1 MOHAWK NOSE GEAR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gage NV1, ND1</strong></td>
</tr>
<tr>
<td>Drag Fwd:</td>
</tr>
<tr>
<td>$F_V = 1,612V - 537D$</td>
</tr>
<tr>
<td>$F_{DF} = -198.2V - 1,536D$</td>
</tr>
<tr>
<td>Drag Aft:</td>
</tr>
<tr>
<td>$F_V = 1,666V + 120.7D$</td>
</tr>
<tr>
<td>$F_{DA} = -137.4V - 1,073D$</td>
</tr>
<tr>
<td><strong>Gage NV1, ND2</strong></td>
</tr>
<tr>
<td>Drag Fwd:</td>
</tr>
<tr>
<td>$F_V = 1,609V - 399.5D_S$</td>
</tr>
<tr>
<td>$F_{DF} = -209.1V - 1,534D_S$</td>
</tr>
<tr>
<td>Drag Aft:</td>
</tr>
<tr>
<td>$F_V = 1,667V + 121.1D_S$</td>
</tr>
<tr>
<td>$F_{DA} = -145.6V - 1,076D_S$</td>
</tr>
<tr>
<td><strong>Gage NV2, ND1</strong></td>
</tr>
<tr>
<td>Drag Fwd:</td>
</tr>
<tr>
<td>$F_V = 1,620V_S - 422.3D$</td>
</tr>
<tr>
<td>$F_{DF} = -199.3V_S - 1,553D$</td>
</tr>
<tr>
<td>Drag Aft:</td>
</tr>
<tr>
<td>$F_V = 1,741V_S + 197.1D$</td>
</tr>
<tr>
<td>$F_{DA} = -143.6V_S - 1,079D$</td>
</tr>
<tr>
<td><strong>Gage NV2, ND2</strong></td>
</tr>
<tr>
<td>Drag Fwd:</td>
</tr>
<tr>
<td>$F_V = 1,617V_S - 421.8D_S$</td>
</tr>
<tr>
<td>$F_{DF} = -210.3V_S - 1,531D_S$</td>
</tr>
<tr>
<td>Drag Aft:</td>
</tr>
<tr>
<td>$F_V = 1,742V_S + 197.8D_S$</td>
</tr>
<tr>
<td>$F_{DA} = -152.2V_S - 1,083D_S$</td>
</tr>
</tbody>
</table>
Use of the Gear Strut Position Transducers

These devices provide an output proportional to the scissors angle of the torque links. Three devices were installed on the landing gears of the YOV-1 Mohawk airplane used in the Rough Terrain Landing Loads Program. The extension of the landing gears is a sinusoidal function of the scissors angle. The equations defining these relationships are as follows:

\[ X_i = 2h \sin \frac{\alpha_i}{2} \]  

\[ X_0 = 2h \sin \frac{\alpha_0}{2} \]  

\[ \alpha_i - \alpha_0 = \beta \]  

\[ RR = \frac{\delta_i - \delta_0}{\Delta}, \delta_0 = 0 \text{ for } X_0 \]  

\[ \beta = K (RR) \]

where

- \( X_i \): distance between torque link pivot points
- \( X_0 \): referenced distance of \( X \) for zero record
- \( h \): length of torque link apex to pivot point
- \( \alpha_i \): included angle between links (scissors angle)
- \( \alpha_0 \): included angle at distance \( X_0 \)
- \( \beta \): excursion angle from reference position
- \( RR \): response ratio
- \( \delta_i \): o'graph deflection for galvo from zero reference position
- \( \Delta \): o'graph deflection for 100KΩ shunt
- \( K \): degrees rotation for 100KΩ shunt

From (1),

\[ \alpha_i = 2 \sin^{-1} \frac{X_i}{2h} \]  

(1a)
From (2),
\[ \alpha_0 = 2 \sin^{-1} \frac{X_0}{2h} \]  
(2a)

From (1a), (2a), (3), and (5),
\[ 2 \left( \sin^{-1} \frac{X_1}{2h} - \sin^{-1} \frac{X_0}{2h} \right) = K(RR) \]  
(6)

where \( RR \) at \( \alpha_0 \) and \( X_0 \) (from Zero record) = 0

Solving for \( X_1 \),
\[ \sin^{-1} \frac{X_1}{2h} = \frac{K(RR)}{2} + \sin^{-1} \frac{X_0}{2h} \]  
(7)

\[ X_1 = 2h \sin \left( \frac{K(RR)}{2} + \sin^{-1} \frac{X_0}{2h} \right) \]  
(7a)

Therefore, any strut position can be determined from the output of these transducers.

**Example** (verification calibration made at Edwards Air Force Base)

\( 2h = 20.376, \frac{1}{2h} = 0.04908, 100K \Omega = 96 \text{ counts} \)

\( K (\text{LMG}, \text{DI #1}) = 44.8 \text{ deg/100K} \Omega \)

Measure zero position of left main strut, \( X_0 = 19.094 \text{ in.} \)

Calculate \( \frac{\alpha_0}{2} \) for \( X_3, \frac{\alpha_0}{2} = 69.6 \text{ deg} \)

Apply \( \delta_i \) readings from oscillograph traces to equations.

\[ \delta_0 = 0 \]
\[ \delta_1 = -215 \quad RR 1 = -2.23 \quad X_1 = 6.85 \text{ in.} \quad 6.900 \text{ in.} \]
\[ \delta_2 = -133 \quad RR 2 = -1.38 \quad X_2 = 12.73 \text{ in.} \quad 12.880 \text{ in.} \]
\[ \delta_3 = -248 \quad RR 3 = -2.58 \quad X_3 = 4.16 \text{ in.} \quad 4.18 \text{ in.} \]

**Constants**

\( 2h \) (main gears) = 20.376 in. \( K_1 \) (DI #1, LMG) = 44.8 deg/100K

\( 2h \) (ncse gears) = 16.376 in. \( K_2 \) (DI #2, RMG) = 45.9 deg/100K

\( K_3 \) (DI #3, NG) = 44.9 deg/100K
STRUT SERVICE

The landing gear was completely assembled and installed in the drop test jig. The strut was fully extended and filled with hydraulic oil (MIL-O-5606) through the strut upper port via a transparent tube leading from an oil container hung above the landing gear jig. The strut was then fully compressed by lowering the drop test jig, causing the excess oil to flow back into the oil container. This procedure was repeated until it was observed through the transparent tube that no air was trapped in the oil flow.

With the strut fully compressed, the oil line was disconnected and the air pressure fitting was installed in the strut upper port and closed. The drop test jig was then raised to allow the wheel to clear the ground by at least 15 inches. The strut was then inflated with nitrogen, causing the piston to fully extend.

Before each series of drops, both tire and strut pressures were checked for the following pressure readings. Similar servicing technique and pressures were applied to the gears in the static calibration jig.

- Main Gear Strut Pressure - 100 psi
- Main Gear Tire Pressure - 90 psi
- Nose Gear Strut Pressure - 75 psi
- Nose Gear Tire Pressure - 65 psi

Maximum Calibration Loads (Static Calibration), Main Gears

The maximum loads were obtained from the strength envelope and are listed in Table IV.

<table>
<thead>
<tr>
<th>Load Direction</th>
<th>Load Sign</th>
<th>Ultimate Load (lb)</th>
<th>Limit Load (lb)</th>
<th>Static Calibration Load (Used) (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>+</td>
<td>37,000</td>
<td>24,667</td>
<td>20,000</td>
</tr>
<tr>
<td>Drag Aft</td>
<td>+</td>
<td>8,000</td>
<td>5,333</td>
<td>5,000</td>
</tr>
<tr>
<td>Drag Fwd</td>
<td>-</td>
<td>19,500</td>
<td>18,000</td>
<td>5,000</td>
</tr>
<tr>
<td>Side Outbd</td>
<td>+</td>
<td>6,920</td>
<td>4,613</td>
<td>4,000</td>
</tr>
<tr>
<td>Side Inbd</td>
<td>-</td>
<td>10,200</td>
<td>6,800</td>
<td>4,000</td>
</tr>
</tbody>
</table>
Strut Extension (Static Calibration)

In all the static calibrations, the strut was extended 2 inches from the fully compressed position.

Maximum Calibration Loads (Static Calibration), Nose Gear

Loads were provided from the strength envelope and are listed in Table V.

<table>
<thead>
<tr>
<th>Load Direction</th>
<th>Sign</th>
<th>Ultimate Load (lb)</th>
<th>Limit Load (lb)</th>
<th>Static Calibration Load (Used) (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>+</td>
<td>30,300</td>
<td>20,200</td>
<td>16,000</td>
</tr>
<tr>
<td>Drag Aft</td>
<td>+</td>
<td>12,600</td>
<td>8,400</td>
<td>4,000</td>
</tr>
<tr>
<td>Drag Fwd</td>
<td>-</td>
<td>7,000</td>
<td>4,670</td>
<td>4,000</td>
</tr>
</tbody>
</table>

Strut Extension (Static Calibration)

The strut was extended 2 inches from the fully compressed position.

LOAD CHANNEL CURVES (Figures 12, 13, and 14)

General

The curves show the axle loads obtained during drop tests of the landing gears. During these drops, the wheels were spun up to simulate landing speeds as follows:

Right main gear, 47 kn
Left main gear, 95 kn
Nose gear, 50 kn

The accuracy of the gear instrumentation can be measured by comparing the loads obtained from separated gage combinations on the same gear, by comparing the loads obtained from gages on one main gear with the loads obtained on the other, and, for vertical loads, by comparing the
gear instrumentation with the drop test platform response. When comparing one main gear load to the other, allowance must be made for the differences in spin-up speed that will affect the drag load appreciably and the vertical and side loads to a minor extent.

Three channels were provided on each main gear for measuring predominantly vertical and drag loads. Two channels were provided on each main gear for measuring side load and two were provided on the nose gear for measuring both vertical and drag loads. Each channel, while responding predominantly to load in one direction, responds to loads in other directions to a lesser extent. Thus, each channel on the main gear has three calibration constants and each channel on the nose gear has two. The main gear loads are obtained from the matrix

\[
V = K_1(\delta/\Delta)_V + K_2(\delta/\Delta)_D + K_3(\delta/\Delta)_S
\]
\[
D = K_4(\delta/\Delta)_V + K_5(\delta/\Delta)_D + K_6(\delta/\Delta)_S
\]
\[
S = K_7(\delta/\Delta)_V + K_8(\delta/\Delta)_D + K_9(\delta/\Delta)_S
\]

where \((\delta/\Delta)_V, D, S\) are the responses of channels measuring predominantly vertical, drag, and side loads and \(K_1\) to \(K_9\) are the aforementioned calibration constants. Since there are 3 channels each producing \((\delta/\Delta)_V\), 3 producing \((\delta/\Delta)_D\), and 2 producing \((\delta/\Delta)_S\), there are 18 ways of obtaining \(V, D,\) and \(S\). The comparisons presented were made using the channels which had the least interaction. Other channels could be used in an emergency.

In the nose gear there is merely a 2x2 matrix; hence, four combinations are available, half of which are presented.

**Right Main Gear** (see Figure 12)

**Vertical load:** The four channel combinations show a variation of \(\pm 7.1/2\%\) from the mean at the peak load. The waves in the platform load are considered platform dynamics and should be ignored. The mean load obtained from gear instrumentation is less than the platform load, but by comparison with the left gear, the gear instrumentation is considered to be more accurate.

**Drag load:** All combinations read nearly the same. This is considered to be excellent.
Side load: Combinations 1, 2, and 3 are in good agreement. Combination 4 is not bad until a vertical load of 12,500 pounds is reached (0.045 set), at which time it deviates considerably. Side load instrumentation in the past has been notably unreliable. In spite of the discrepancies shown here, this was the best side instrumentation obtained to date.

**Left Main Gear (see Figure 13)**

Vertical load: Accuracy is excellent.

Drag load: Combinations 1, 2, and 4 are good. Combination 3 gives good maximum load but poor shape. Comparison with the right gear indicates that the shape of 1, 2, and 4 is correct.

Side load: Combinations 1, 2, and 3 agree well. Combination 4 is no good. The comment on right gear side load instrumentation is applicable.

Generally, the side load instrumentation will go bad when the vertical load is high because the tire becomes fully compressed and the vertical load is carried largely by one wheel flange. This affects the side reading as noted in the matrix (page 13).

**Nose Gear (see Figure 14)**

Both vertical and drag instrumentation are considered excellent. The difference between platform reading and strain gage reading is considered to be caused by poor dynamic response of the platform (see Figure 9c). The quality of the nose gear instrumentation shows the advantage of instrumenting a gear with a symmetrical fork.

Table VI lists the best combinations of channels and the corresponding recommended calibration constants.
<table>
<thead>
<tr>
<th>Table VI. Best Channel Combinations and Recommended Calibration Constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMG</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>$V$</td>
</tr>
<tr>
<td>$D$</td>
</tr>
<tr>
<td>$S$</td>
</tr>
<tr>
<td>RMG</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>$V$</td>
</tr>
<tr>
<td>$D$</td>
</tr>
<tr>
<td>$S$</td>
</tr>
<tr>
<td>NG</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>$V$</td>
</tr>
<tr>
<td>$D$</td>
</tr>
</tbody>
</table>

15
The Douglas instrumentation drawings are listed in Table VII.

<table>
<thead>
<tr>
<th>Drawing Number</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>14245</td>
<td>Oil Pressure Pick Up Housing Plug</td>
</tr>
<tr>
<td>14250</td>
<td>Oil Pressure Pick Up Plug Safety Strap</td>
</tr>
<tr>
<td>14255</td>
<td>Air Pressure Outlet Adapter</td>
</tr>
<tr>
<td>14257</td>
<td>Side Wheel Tire - Drop Carriage</td>
</tr>
<tr>
<td>14258</td>
<td>Center Wheel Tire - Drop Carriage</td>
</tr>
<tr>
<td>14264</td>
<td>Air Pressure Pick Up Adapter</td>
</tr>
<tr>
<td>14268</td>
<td>Wheel Spacer</td>
</tr>
<tr>
<td>14269</td>
<td>Wheel Grease Seal</td>
</tr>
<tr>
<td>14281</td>
<td>Air Pressure Pick Up Tee</td>
</tr>
<tr>
<td>14284</td>
<td>Air Bucket Plate Lugs - Spin Up</td>
</tr>
<tr>
<td>14285</td>
<td>Stroke Transducer Lower Attach Bracket - Drop Test</td>
</tr>
<tr>
<td>14286</td>
<td>Stroke Transducer Attach Bracket - Drop Test</td>
</tr>
<tr>
<td>14287</td>
<td>Stroke Transducer Attach Bracket - Drop Test</td>
</tr>
<tr>
<td>14288</td>
<td>Stroke Transducer Attach Bracket Spacers - Drop Test</td>
</tr>
<tr>
<td>14291</td>
<td>Dummy Brake Keys</td>
</tr>
<tr>
<td>22885</td>
<td>Strut Side Brace Support Jig</td>
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<td>22886</td>
<td>Metering Pin Support - Oil Press. Pick Up Rework</td>
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<tr>
<td>22887</td>
<td>Oil Pressure Pick Up Housing</td>
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<td>22888</td>
<td>Oil Pressure Pick Up Installation</td>
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<tr>
<td>22900</td>
<td>Side Brace - Upper End Fitting</td>
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<tr>
<td>22901</td>
<td>Side Brace - Lower End Fitting</td>
</tr>
<tr>
<td>22904</td>
<td>Dummy Tire</td>
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<tr>
<td>22908</td>
<td>Side Load Pull-Off Fixture</td>
</tr>
<tr>
<td>22909</td>
<td>Lower Mass-Vertical &amp; Drag Accelerometer Housing</td>
</tr>
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<td>31393</td>
<td>Drop Test Column Installation</td>
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<td>Gear Installation in Drop Test Columns</td>
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<tr>
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<td>Main Strut Support Jig</td>
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<td>Small Drop Test Carriage</td>
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<td>41404</td>
<td>Dummy Side Brace Assembly</td>
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<td>Lower Mass Accelerometer Installation</td>
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<td>Drag Load Pull-Off Fixture</td>
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<td>Air Bucket Plate - Spin-Up</td>
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<td>41432</td>
<td>Stroke Transducer Installation - Drop Test</td>
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<td>Z7825491</td>
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<tr>
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The YOV-1 Mohawk landing gear drawings are listed in Table VIII.

### TABLE VII. Continued

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<td>Phase III - Drop Tests</td>
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<td>Z5891061</td>
<td>YOV-1 Mohawk Landing Gear Calibration Jig</td>
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<td>Z4891071</td>
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<td>Z4891072</td>
<td>Rework of Support Jig</td>
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<tr>
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<td>Dummy Drag Brace</td>
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### TABLE VIII. YOV-1 MOHAWK LANDING GEAR DRAWINGS

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<td>172315</td>
<td>Shock Strut Assembly</td>
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<tr>
<td>172481</td>
<td>Piston (Machining)</td>
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<td>172493</td>
<td>Adapter - Upper Bearing</td>
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<tr>
<td>172496</td>
<td>Bearing - Lower</td>
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<tr>
<td>172601</td>
<td>Valve - Snubber</td>
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<tr>
<td>172602</td>
<td>Bearing - Upper</td>
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<tr>
<td>172605</td>
<td>Tube - Orifice Support</td>
</tr>
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<td>172608</td>
<td>Fitting - Lower End</td>
</tr>
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<td>173487</td>
<td>Orifice</td>
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<tr>
<td>173545</td>
<td>Cylinder - Outer</td>
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<td>172762</td>
<td>Fitting - Orifice</td>
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<td>173483</td>
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<td>Cam - Lower</td>
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<td>Key</td>
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<td>172771</td>
<td>Bearing</td>
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<td>Cam - Upper</td>
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**Bendix Co.**

**NOSE GEAR (contd)**

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<td>Main Gear Installation</td>
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<td>134L10001, Sheet 2</td>
<td>Main Gear Installation</td>
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<tr>
<td>134PD10011</td>
<td>General Arrangement - Alighting Gear</td>
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<tr>
<td>134PD10014</td>
<td>Main Gear Geometry</td>
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**Grumman Co.**

**MAIN GEAR**

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<tr>
<td>134L10002, Sheet 2</td>
<td>Nose Gear Installation</td>
</tr>
<tr>
<td>134PD10013</td>
<td>Geometry (Proposed) Alighting Gear - Nose Gear</td>
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BRIDGE DATA

CHANNEL NUMBER  LV - 1
GAGE TYPE       SA-06-250BF-350 (13-36)
GAGE RESISTANCE 350 Ohms
MAXIMUM VOLTAGE 5

CALIBRATION DATA

RESISTANCE ACROSS PINS SENSITIVITY
 100K Ohms 1 & 2

Figure 2. Typical Bridge Circuit.
Figure 3. Strain Gage Installation - Nose Gear Axle.
NOTE:
BRIDGES ARE COMPLETED AT TERMINALS.
PROVIDE (4 COND) NO. 22 SHIELDED LEADS TERMINATED WITH FULL LUGS.
"D" DESIGNATES DUMMY STRAIN GAGES.

Figure 4. Left Main Gear Strain Gage Wiring Details.
Figure 5. Left Main Gear Miniature Cannon Connector Wiring.

NOTE:
CONNECTOR IS REQUIRED TO PERMIT BRAKE CHANGES.
Figure 6. Static Calibration - Main Gears.
Figure 8. Typical Drop Record.
Figure 9. Drop Test Setup - Nose Gear.
Figure 10. Air Pressure Pickup Installation.
Figure 11. Strut Position Transducer Calibration Curve.
Figure 12. Load Response Curves - Right Main Gear.
Figure 13. Load Response Curves - Left Main Gear.
Figure 14. Load Response Curves - Nose Gear.
SECTION II. FIELD TESTS

ROUGH FIELD MEASUREMENTS

Contour measurements of selected sod field landing sites at Camp Pickett, Franklin, and Petersburg, Virginia, were performed to obtain actual roughness data for correlating the mathematical expressions related to the gear dynamics during landings and rollouts. These data were used to modify those portions of the computer program where correlation was not obtained for each analytical printout. That is, for each particular landing, the aircraft was mathematically flown to a landing. These results were then compared to and correlated with the actual measured test data.

The profilometer system used in the field measurements has been well documented in TRECOM Technical Report 64-19 (Reference 1), and consists of a collimated light source, contour tracker (including light beam sensor), and both hydraulic and electrical power supply and controls. The surface roughness sensed by the tracker was recorded in digital form on paper tape which was then converted to IBM card format for computer processing. A segment of one of the numerous elevation plots of the Franklin field landing site is shown in Figure 15.

In order to provide further data on relative roughness, the Air Force was requested to reduce the profile data to power spectral density form. Appendix II is a report of the result of this analysis for the Franklin and Camp Pickett, Virginia, test sites.

Soil penetration measurements were made throughout the 48-foot by 100-foot target touchdown area and immediately adjacent to the aircraft's touchdown and roll tracks within this area. A mobility cone penetrometer having a 30-degree cone with a 0.5-square-inch base area was used to measure the soil bearing strength. Readings obtained at the time of the crash landing ranged from a low of 80 to a high of 121 psi.

AIRCRAFT INSTRUMENTATION

Three 18-channel oscillograph recorders were installed in the camera and baggage compartment areas to record in-flight and landing dynamic behavior of the airframe and landing gear. Except for the forward and sink-speed radar velocimeters, the instrumentation system was typical of general flight-test practice in that the various parameter measurements were satisfied by the use of stock sensors and recorders. Appendix III is a schematic of the test instrumentation circuitry reflecting the
parameters measured and the system components.

With respect to the special radar units, signal conditioners were designed to permit recording as well as indications to the pilot of his approach slant and sink speeds. Special cockpit panel meters were installed to aid the pilot in trimming the aircraft to satisfy the desired approach velocities. The functional theory for these devices is described in Appendix IV.

LANDINGS

Although three sod landing fields of increasing roughness were selected and contour measured at Franklin, Petersburg, and Camp Pickett, Virginia, only the former was used because of a landing accident. Since the accident occurred on the initial planned landing (on 3 August 1967), the two landings previously performed (on 18 July and 2 August) as pilot's proficiency and instrumentation qualification tests were necessarily used as sources for correlation and evaluation of the Douglas mathematical landing gear model. Certain parameter values, therefore, such as aircraft pitch and roll attitude, were intuitively determined to permit conduct of the mathematical analyses, since all measured data channels were not functional at these times. Table XV provides a summary of the adequacy of the measured parameters for analysis purposes.

Of the three landings evaluated, the 2 August landing was made on the concrete strip adjacent to the sod test area while the 18 July and 3 August landings were performed adjacent to and within the sod test area, respectively. Figure 16 depicts the physical relation of the three landing areas described, while Figure 17 shows the three simultaneous oscillograph records acquired for the crash landing of 3 August. Although 0.13 second of time elapsed from nose gear touchdown to loss of various signal traces, the separation of wheel strut caused severance of signal-carrying wires; therefore, the strut failure had to occur some time immediately prior to the wire failure. The mathematical simulation of this landing agrees with this reasoning in that gear failure was predicted to begin 0.06 second after contact of the nose wheel and ground. A close-up of the aircraft nose and the failed nose gear strut is shown in Figure 18.
Figure 15. Roughness Plot of Franklin Field Landing Site.
Figure 18. View of Failed Nose Gear Strut.
METHOD OF ANALYSIS

The calculated loads presented herein were obtained from a dynamic loads computing program in which the gear and airplane were considered as mutually interacting dynamic systems and in which the gear operating characteristics and airplane motion were simulated mathematically. The equations of motion in Appendix I were solved by means of numerical integration on the IBM 360 computer.

The computer program is based on those described in References 2 and 3; however, many extensions and refinements have been added, the most important of which are:

1. Pretouchdown calculations are included. The airplane is balanced in accordance with normal aerodynamic procedures and in conformance with the initial conditions established by the test data. Mathematically, the airplane is then "flown" in for the landing.

2. Pitch and roll degrees of freedom have been added to the airplane motion. These are in addition to the vertical and fore and aft translational degrees incorporated previously in References 2 and 3.

3. Provision has been made for inserting the contour of the ground into the program by a series of coordinates, thus making it possible to use any contour rather than only those that can be easily described mathematically.

4. The program uses a variable integration interval that is chosen automatically to give the required accuracy considering the rapidity of the motion. The interval is permitted to vary between 0.002 and 0.000008 second.

5. Refined equations have been incorporated for side and drag loads on the gear as well as for strut torsion.

6. New concepts of sliding and rolling coefficients of friction of the tire on the ground have been incorporated (see page 56).
7. Changes were made, as necessary, to adapt the program to the IBM 360 computer (was IBM 7094).

The computer was directed to print out significant items of information every 0.002 second. The input required is shown in Tables IX through XII. Items of output obtained from the program are listed in Table XIII.

Computing time averaged 3 minutes for a landing impact involving 0.3 second of real time and 25 minutes for a landing impact plus rollout covering 150 feet of rough runway (approximately 1.2 seconds of real time).

**LANDINGS SIMULATED**

Loads were computed for three landings (see Figures 19 through 32):

1. 18 July 1967 - landing on sod at the airfield in Franklin, Virginia.

2. 2 August 1967 - landing on concrete at the airfield in Franklin, Virginia.

3. 3 August 1967 - landing on sod at the airfield in Franklin, Virginia (the nose gear failed, resulting in strike damage to the aircraft).

Initial conditions for these landings are provided in Table XIV. Most of the data in this table was obtained directly from measurements. The rest was deduced from measurements, either with or without the aid of supplementary calculations as described in the following section.

In addition to the above three landings, calculations are provided for the following:

1. An 8-foot-per-second landing and subsequent rollout for 150 feet on a rough part of the Franklin field sod strip (contour shown in Figure 33).

2. An 8-foot-per-second landing and subsequent rollout for 150 feet on a rough portion of the Camp Pickett field sod strip (Site I) (contour shown in Figure 33).

Comparison of the load time-histories of these landings and rollouts shows the effect on landing gear loads of terrain of varying degrees of
SECTION III. COMPUTED LOADS AND COMPARISON WITH TEST RESULTS

METHOD OF ANALYSIS

The calculated loads presented herein were obtained from a dynamic loads computing program in which the gear and airplane were considered as mutually interacting dynamic systems and in which the gear operating characteristics and airplane motion were simulated mathematically. The equations of motion in Appendix I were solved by means of numerical integration on the IBM 360 computer.

The computer program is based on those described in References 2 and 3; however, many extensions and refinements have been added, the most important of which are:

1. Pretouchdown calculations are included. The airplane is balanced in accordance with normal aerodynamic procedures and in conformance with the initial conditions established by the test data. Mathematically, the airplane is then "flown" in for the landing.

2. Pitch and roll degrees of freedom have been added to the airplane motion. These are in addition to the vertical and fore and aft translational degrees incorporated previously in References 2 and 3.

3. Provision has been made for inserting the contour of the ground into the program by a series of coordinates, thus making it possible to use any contour rather than only those that can be easily described mathematically.

4. The program uses a variable integration interval that is chosen automatically to give the required accuracy considering the rapidity of the motion. The interval is permitted to vary between 0.002 and 0.000008 second.

5. Refined equations have been incorporated for side and drag loads on the gear as well as for strut torsion.

6. New concepts of sliding and rolling coefficients of friction of the tire on the ground have been incorporated (see page 56).
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1. An 8-foot-per-second landing and subsequent rollout for 150 feet on a rough part of the Franklin field sod strip (contour shown in Figure 33).

2. An 8-foot-per-second landing and subsequent rollout for 150 feet on a rough portion of the Camp Pickett field sod strip (Site I) (contour shown in Figure 33).

Comparison of the load time-histories of these landings and rollouts shows the effect on landing gear loads of terrain of varying degrees of
roughness as predicted by the computer. The calculations for these two landings were made for an ideally "hard" surface; i.e., no deformation of the contour was considered.

LIMITATIONS IMPOSED BY AVAILABLE DATA

Since the instrumentation was still in the process of being debugged when the crash landing occurred, several channels were not working consistently or were not adequately zeroed during the three landings under investigation. Table XV lists the various channels and classifies the data as being satisfactory, not available, lacking a zero, or questionable.

For the 18 July and 2 August landings, lack of knowledge concerning the exact point of touchdown was most serious. This void in the data made it impossible to insert the terrain contour in the calculations, and it was questionable whether some of the load discrepancies were caused by surface irregularities or inappropriate assumptions in the calculations. Comparisons of calculated and measured loads will show, however, that the differences are no greater than those obtained in the test program of Reference 3, in which the terrain was known precisely.

Also, the zeros for the roll and pitch attitude were not known precisely. This deficiency was overcome by noting the time relationships for touchdown of the left and right gears in the case of roll and between the main and nose gears in the case of pitch.

No nose gear vertical load was reported for the 18 July landing, and since the drag load is dependent to a certain extent upon the vertical channel reading (see Table III), the accuracy of the drag load is questionable.

The nose gear load traces on the 3 August landing quickly went beyond the boundary of the record, so that the time of touchdown of the nose gear and the initial slopes of the load curves are the only data salvaged from the nose gear traces. The exact time of failure was somewhat difficult to determine. In fact, with a bending-type failure there is probably a substantial interval between the onset of permanent deformation and the separation of the part. From study of the records and the calculations, it is estimated that failure began at 0.06 second after initial touchdown and was complete at 0.15 second. The piston fracture came at a point corresponding to a stroke of 9 inches from fully extended; however, failing loads probably occurred several inches sooner.
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<th>Symbol</th>
<th>FORTRAN Notation</th>
<th>Input Value</th>
<th>Units</th>
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<td>Ratio of elevator angle to horizontal stabilizer angle</td>
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<td></td>
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<tr>
<td>Engine thrust</td>
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<td>lb</td>
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<td>$\varepsilon \leq 2 \frac{</td>
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<td>X_p</td>
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Gear Constants

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<th>Left Main Gear</th>
<th>Right Main Gear</th>
<th>Nose Gear</th>
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<td>Lateral location</td>
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<td>in.</td>
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<td>Weight of unsprung portion of strut (wheel, brakes, piston, etc.)</td>
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<td>WU</td>
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<td>lb</td>
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<td></td>
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<td>Angle of strut perpendicular to FRL (forward)</td>
<td>phi</td>
<td>PHI</td>
<td>1.5 1.5 -5.208</td>
<td>deg</td>
<td></td>
<td></td>
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<td>Angle of strut perpendicular to FRL (clockwise looking forward)</td>
<td>sigma</td>
<td>SIGMA</td>
<td>2.2 -2.2 0.0</td>
<td>deg</td>
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<td>Distance from strut attach point to axle, strut fully extended</td>
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<td>EL</td>
<td>65.0 65.0 44.2</td>
<td>in.</td>
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<td>Axle offset to left side of strut center line</td>
<td>eb</td>
<td>EB</td>
<td>0.0 0.0 0.0</td>
<td>in.</td>
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<td></td>
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<tr>
<td>Distance between lower bearing and axle (strut extended)</td>
<td>ABRG</td>
<td>ABRG</td>
<td>37.06 37.06 26.73</td>
<td>in.</td>
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<td></td>
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<tr>
<td>Distance between upper and lower bearings (strut extended)</td>
<td>BBRG</td>
<td>BBRG</td>
<td>10.5 10.5 7.05</td>
<td>in.</td>
<td></td>
<td></td>
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<tr>
<td>Aft deflection of strut for a unit load parallel to strut</td>
<td>K1</td>
<td>K1</td>
<td>0.0 0.0 1.01x10^-5</td>
<td>in./lb</td>
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<tr>
<td>Stiffness of strut in aft direction due to an aft deflection</td>
<td>K32</td>
<td>K32</td>
<td>2860.0 2860.0 2400.0</td>
<td>lb/in.</td>
<td></td>
<td></td>
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<tr>
<td>Stiffness of strut in aft direction due to an aft deflection</td>
<td>K33</td>
<td>K33</td>
<td>119.0 119.0 327.0</td>
<td>lb/in.^2</td>
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\[ F = (K_{32} + S K_{33})^6 \]
<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>FORTRAN Notation</th>
<th>Input Value</th>
<th>Units</th>
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<tr>
<td></td>
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<td></td>
<td>Left Main Gear</td>
<td>Right Main Gear</td>
</tr>
<tr>
<td>Side deflection of strut for a unit load parallel to strut</td>
<td>$K_4$</td>
<td>K4</td>
<td>0.00001</td>
<td>0.00001</td>
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<td>Stiffness of strut in side direction due to a side deflection</td>
<td>$K_{22}$</td>
<td>K22</td>
<td>5500.0</td>
<td>5500.0</td>
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<td>$K_{23}$</td>
<td>K23</td>
<td>921.0</td>
<td>921.0</td>
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<td>Torsional stiffness of strut</td>
<td>$K_\beta$</td>
<td>KBETA</td>
<td>4.7x10⁶</td>
<td>4.7x10⁶</td>
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<td>Torsional inertia of strut about strut center line</td>
<td>$I_\beta$</td>
<td>IBETA</td>
<td>20.0</td>
<td>20.0</td>
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<tr>
<td>Aft direction</td>
<td>$\bar{C}$</td>
<td>CBAR</td>
<td>4.0</td>
<td>4.0</td>
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<tr>
<td>Side direction</td>
<td>$C_S$</td>
<td>CS</td>
<td>20.0</td>
<td>20.0</td>
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<td></td>
<td>$C_\beta$</td>
<td>CBETA</td>
<td>160.0</td>
<td>160.0</td>
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<td>Ground side coefficient of friction</td>
<td>$\mu_\psi$</td>
<td>MUPSI</td>
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<td>0.5</td>
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<td>Lateral stiffness of tire</td>
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<td>10000.0</td>
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<td>Torsion angle of tire</td>
<td>$r_T$</td>
<td>RT</td>
<td>13.06</td>
<td>13.06</td>
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<td>Maximum tire deflection</td>
<td>$C_{T_{max}}$</td>
<td>CTN</td>
<td>9.0</td>
<td>9.0</td>
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<td>Mass inertia of rolling assembly</td>
<td>$I_R$</td>
<td>IR</td>
<td>7.55</td>
<td>7.55</td>
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<td>Input Value</td>
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<tr>
<td>Factor for effective rolling radius</td>
<td>$e_r$</td>
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<tr>
<td>Maximum strut stroke</td>
<td>$S_{max}$</td>
<td>SN</td>
<td>15.0</td>
<td>in.</td>
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<tr>
<td>Density of hydraulic fluid in strut</td>
<td>$p_o$</td>
<td>RHO</td>
<td>$0.777 \times 10^{-4}$</td>
<td>lb $\cdot$ sec$^2$</td>
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<tr>
<td>Value of strut velocity for changing from static to sliding friction at bearings</td>
<td>$S_S$</td>
<td>SS</td>
<td>2.0</td>
<td>in. /sec</td>
</tr>
<tr>
<td>Orifice area</td>
<td>$A_o$</td>
<td>AO</td>
<td>0.4418</td>
<td>in.$^2$</td>
</tr>
<tr>
<td>Internal area of oleo piston</td>
<td>$A_1$</td>
<td>A1</td>
<td>9.294</td>
<td>in.$^2$</td>
</tr>
<tr>
<td>Area of piston outer diameter</td>
<td>$A_{pod}$</td>
<td>APOD</td>
<td>12.566</td>
<td>in.$^2$</td>
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<tr>
<td>Air load in fully extended strut (pressure x $A_{pod}$)</td>
<td>$P_E$</td>
<td>PE</td>
<td>1231.0</td>
<td>lb</td>
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<tr>
<td>Volume of air in fully extended strut</td>
<td>$V_{ea}$</td>
<td>VEA</td>
<td>207.3</td>
<td>in.$^3$</td>
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<td>Polytropic exponent for calculation of strut air load</td>
<td>$n_1$</td>
<td>N1</td>
<td>1.12</td>
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<tr>
<td>Distance from wheel center line to left of fork center line</td>
<td>$e_x$</td>
<td>EX</td>
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<td>in.</td>
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### TABLE X. AERODYNAMIC DATA

<table>
<thead>
<tr>
<th>Airplane Angle of Attack (deg)</th>
<th>$C_L$</th>
<th>$C_D$</th>
<th>$C_{M_{ac}}$</th>
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<tr>
<td>-1.5</td>
<td>0.766</td>
<td>0.160</td>
<td>-0.0600</td>
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<tr>
<td>0.5</td>
<td>0.958</td>
<td>0.184</td>
<td>-0.0888</td>
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<tr>
<td>2.5</td>
<td>1.150</td>
<td>0.208</td>
<td>-0.1176</td>
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<tr>
<td>4.5</td>
<td>1.342</td>
<td>0.238</td>
<td>-0.1464</td>
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<tr>
<td>6.5</td>
<td>1.534</td>
<td>0.272</td>
<td>-0.1752</td>
</tr>
<tr>
<td>8.5</td>
<td>1.726</td>
<td>0.308</td>
<td>-0.2040</td>
</tr>
<tr>
<td>10.5</td>
<td>1.918</td>
<td>0.357</td>
<td>-0.2328</td>
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<tr>
<td>12.5</td>
<td>2.020</td>
<td>0.406</td>
<td>-0.2616</td>
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<tr>
<td>14.5</td>
<td>2.050</td>
<td>0.455</td>
<td>-0.2904</td>
</tr>
</tbody>
</table>

Mean aerodynamic chord \( \overline{c} = 98.0 \) in.

Wing area \( S_W = 330.75 \) ft\(^2\)

Change in airplane lift coefficient per unit elevator angle \( \frac{dC_L}{d\delta_e} = 0.0065/\) deg

Change in airplane moment coefficient per unit elevator angle \( \frac{dC_{M_{ac}}}{d\delta_e} = -0.018/\) deg

* Parameters are assumed to vary linearly between points noted.
### TABLE XI. TIRE LOAD DEFLECTION DATA

<table>
<thead>
<tr>
<th>Main Gears</th>
<th>Nose Gear</th>
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<tr>
<td><strong>Deflection (in.)</strong></td>
<td><strong>Load (lb)</strong></td>
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<td>0.0</td>
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<td>1.946</td>
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<td>5.520</td>
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<td>24300.0</td>
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<td>6.500</td>
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<tr>
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<tr>
<td>4.550</td>
<td>14000.0</td>
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* A linear variation is assumed between points noted.

---

### TABLE XII. METERING PIN DIAMETERS

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<thead>
<tr>
<th>Main Gears</th>
<th>Nose Gear</th>
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<tbody>
<tr>
<td><strong>Stroke (in.)</strong></td>
<td><strong>Diameter (in.)</strong></td>
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<td>0.00</td>
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<tr>
<td>2.80</td>
<td>0.640</td>
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<td>5.80</td>
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<tr>
<td>12.88</td>
<td>0.687</td>
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<tr>
<td>15.40</td>
<td>0.687</td>
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* Diameter varies linearly between points noted.
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<th>Item</th>
<th>Nomenclature</th>
<th>Unit</th>
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<td>Center of gravity motion relative to airplane axes, from t=0:</td>
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<tr>
<td>Vertical</td>
<td>H-DISP</td>
<td>H-VEL</td>
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<tr>
<td>Fore and Aft</td>
<td>F-DISP</td>
<td>F-VEL</td>
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<tr>
<td>Pitch</td>
<td>A-DISP</td>
<td>A-VEL</td>
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<tr>
<td>Roll</td>
<td>T-DISP</td>
<td>T-VEL</td>
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<tr>
<td>Aerodynamic loads at airplane center of gravity:</td>
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</tr>
<tr>
<td>Lift</td>
<td>AIR-1</td>
<td>lb</td>
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<tr>
<td>Pitch</td>
<td>AIR-2</td>
<td>in. -lb</td>
</tr>
<tr>
<td>Roll</td>
<td>AIR-3</td>
<td>in. -lb</td>
</tr>
<tr>
<td>Drag</td>
<td>AIR-4</td>
<td>lb</td>
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<tr>
<td>Aerodynamic loads at aerodynamic center:</td>
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<td></td>
</tr>
<tr>
<td>Lift</td>
<td>ALIFT</td>
<td>lb</td>
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<tr>
<td>Pitch</td>
<td>APITCH</td>
<td>in. -lb</td>
</tr>
<tr>
<td>Drag</td>
<td>ADRAG</td>
<td>lb</td>
</tr>
<tr>
<td>Engine thrust</td>
<td>THRUST</td>
<td>lb</td>
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<tr>
<td>Center of gravity locations relative to ground axes, from t=0:</td>
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<tr>
<td>Vertical</td>
<td>DCG</td>
<td>in.</td>
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<tr>
<td>Horizontal</td>
<td>UCG</td>
<td>in.</td>
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<td>Center of gravity velocities:</td>
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<tr>
<td>Vertical</td>
<td>VZ</td>
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<td>Axial strut load</td>
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<tr>
<td>Strut air load</td>
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<tr>
<td>Strut oil load</td>
<td>PO</td>
<td>lb</td>
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<tr>
<td>Strut friction load</td>
<td>PF</td>
<td>lb</td>
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<tr>
<td>Strut normal drag load</td>
<td>FD</td>
<td>lb</td>
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<tr>
<td>Strut normal side load</td>
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</tr>
<tr>
<td>Strut torque</td>
<td>TBETA</td>
<td>in. -lb</td>
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<tr>
<td>Tire load normal to local ground</td>
<td>PV</td>
<td>lb</td>
</tr>
<tr>
<td>Tire load parallel to local ground (drag)</td>
<td>PD</td>
<td>lb</td>
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<table>
<thead>
<tr>
<th>Item</th>
<th>Nomenclature</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Vertical tire load</td>
<td>PT</td>
<td>lb</td>
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<td>Horizontal tire load (drag)</td>
<td>MUPT</td>
<td>lb</td>
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<tr>
<td>Horizontal tire load (side)</td>
<td>PS</td>
<td>lb</td>
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<td>Tire deflection</td>
<td>CT</td>
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<tr>
<td>Orifice coefficient</td>
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<td>-</td>
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<td>Radial clearance between metering pin and orifice</td>
<td>ANN</td>
<td>in.</td>
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<tr>
<td>Oil velocity through orifice</td>
<td>VO</td>
<td>in./sec</td>
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<td>Upper bearing normal load</td>
<td>F1TOT</td>
<td>lb</td>
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<td>Upper bearing load:</td>
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<td>Drag direction</td>
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<td>Lower bearing normal load</td>
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<td>Vertical deflection of top of strut due to airplane flexibility relative to center of gravity</td>
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<td>rad, sec</td>
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<td>Rotation about axle</td>
<td>DISP, VEL, ACC - OMEGA</td>
<td>rad, sec</td>
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<td>Slip ratio</td>
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<td>Sliding coefficient of friction (tire on ground)</td>
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<td>Axle acceleration parallel to strut (total)</td>
<td>ACC-AA</td>
<td>in./sec^2</td>
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<td>Acceleration of axle normal to strut:</td>
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<tr>
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<td>ACC-DD</td>
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<td>Side</td>
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<td>Elastic motion of axle normal to strut relative to airplane:</td>
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<td>Side</td>
<td>DISP, VEL, ACC - BBAR</td>
<td>in., sec</td>
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<td>Units</td>
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<td>Deflection of strut due to axial load:</td>
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<td>Side</td>
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<td>in., sec</td>
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<tr>
<td>Vertical</td>
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<tr>
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<td>VY</td>
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<td>Airplane sink speed, perpendicular to horizontal</td>
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<td>Velocity of head wind</td>
<td>V_w</td>
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<td>Angle of FRL with respect to horizontal (pitch attitude) (+ nose up)</td>
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<td>A</td>
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<td>Airplane pitching rate (+ nose up)</td>
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<td>Roll attitude of airplane (+ left wing down)</td>
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<td>Drag</td>
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<td>S</td>
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<td>Drag</td>
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<tr>
<td>Right</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Wing Tip Acceleration</td>
<td></td>
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<tr>
<td>Left</td>
<td>NA</td>
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<td>Right</td>
<td>NA</td>
<td>S</td>
</tr>
<tr>
<td>Airplane Velocities</td>
<td></td>
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<tr>
<td>Horizontal</td>
<td>S</td>
<td>Q</td>
</tr>
<tr>
<td>Vertical</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Airplane Attitude</td>
<td></td>
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</tr>
<tr>
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<td>N-0</td>
</tr>
<tr>
<td>Roll</td>
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<td>S</td>
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<tr>
<td>Roll</td>
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<td>Q</td>
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<tr>
<td>Airplane Accelerations</td>
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<td>S</td>
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<tr>
<td>Pilot Station</td>
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<td>S</td>
</tr>
<tr>
<td>Wheel Position Pip</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Elevator Position</td>
<td>S</td>
<td>S</td>
</tr>
</tbody>
</table>

S-Satisfactory; Q-Questionable; NA-Not Available; N-O, No Zero
Failure of the nose gear was duplicated on the computer by reducing the nose gear vertical load drastically at 0.07 second after touchdown. This was accomplished by arbitrarily reducing the ground elevation under the nose gear at that time. Main gear loads were then calculated for another 0.2 second. The measured stroke on the nose gear for the 3 August landing is considered to be questionable, since no stroke is recorded for 0.03 second after nose gear impact, as determined from load and accelerometer traces.

The sink-speed indicator (page 33) measured the relative vertical speed of the airplane and the ground. The device was quite accurate; however, when the airplane flew over rough terrain, the ground reference changed with airplane horizontal position, and an irregular record was produced. The irregular readings obtained from the 18 July and 3 August landings produced a source of possible error. Values used in the calculations were obtained by consideration of both the sink-speed indicator readings and the total energy in the measured load-stroke diagrams of the gears.

UNUSUAL PHENOMENA

On examination of the test data, several unusual phenomena were noted that required changes or additions to the computing program. This was to be expected with regard to the rough field landings; in fact, the discovery of such phenomena was one of the purposes of the test program. However, the first problem occurred with the concrete landing and consisted of a marked difference between the behavior of the right and left gears. This difference is illustrated by Figure 19, which compares the vertical loads obtained from the two gears.

The left gear behaved in what was considered to be a standard manner, and the loads could be predicted by the computer without difficulty. The right gear vertical load displayed a low average value combined with an extended stroke. Load pulses were superimposed on the average load curve at regular intervals, as though the gear were running over a series of small bumps. Examination of the oil chamber pressure and axle acceleration traces confirmed that the pulses were real and not a product of malfunctioning instrumentation. Examination of the right gear stroke-time curve showed an initial slope that was higher than expected for the measured airplane sinking speed. The right gear's behavior resembled that observed on a nose gear of another airplane. This behavior, which was caused by air in the chamber below the orifice at the time of impact, occurred when the gear was lowered immediately before touchdown. In other words, in the retracted position, oil flowed into the air chamber above the orifice and did not have sufficient time to flow back between the
time of gear extension and touchdown. Whether this was the problem with the Mohawk right gear during this particular landing is not known, but the average load curve could be predicted reasonably well if the fluid density in the orifice flow equation was reduced radically for the first 4.4 inches of stroke. Treating the right gear in this manner permitted a satisfactory calculation of the left gear loads, the airplane motion between main and nose gear touchdown, and the nose gear loads. The computing program was not able to predict all ramifications of the right main gear loads without major modification, and extended effort was not made to duplicate those loads in detail.

The "failure landing" of 3 August 1967 produced unusual main gear load records, as shown in Figure 28. The flat spots at "A" and "B" are considered to be associated with failure of the soil underneath the gears. Static and dynamic tests of soils have shown that they have load deflection curves similar to those in Figure 34, obtained from Reference 4. The ultimate strength undoubtedly varies with moisture content; on an unprepared field recently subjected to a rainfall, the moisture content could vary from point to point. This theory is offered as an explanation of the difference in strength between the left and right gears as noted in the load-time curves of Figure 28. The method of accounting for soil deformation and its effect on gear loads is described in the following section.

EFFECT OF SOIL DEFORMATION ON GEAR LOADS

Calculation of Soil Deformation for the 3 August Landing

The characteristics of soils depicted by Figure 34 can be duplicated qualitatively by a nonlinear spring-mass-damper mechanical system. Early attempts at duplicating the loads for the 3 August landing consisted of representing the soil by a nonlinear spring only. They were not successful because the calculated main gear drag loads tended to build up in phase with the vertical loads; whereas in the measured loads, the drag lagged considerably behind the vertical (see Figure 28).

The computer required a tire load versus soil deflection curve input rather than a soil pressure versus deflection curve input. It is pertinent to examine qualitatively the shape of this curve. To do this, it is necessary to know the nature of the soil pressure versus tire load curve. Up to the point of tire bottoming, the footprint pressure of a tire is approximately constant and equal to the inflation pressure, \( P_0 \). Loads in excess of the tire-bottoming load \( P_{TB} \) increase the footprint pressure so that

55
The effective area, $A$, on which $P_T - P_{TB}$ operates is somewhat less than the normal footprint area because the loads tend to concentrate under the rim. Figure 31 shows the qualitative pressure-load relationship. The dotted line to the left indicates that the transition to $p_0$ is something other than a step function. This occurs at small tire deflections, and its exact nature is not important to this problem.

Figure 36 shows the qualitative tire load versus soil deflection curves derived from the soil curves presented and the tire load/soil pressure curve of Figure 35. The relationship between $P_{TB}$ and $P_T$ at failure in these two curves is approximately the same as that observed in the records for the left and right gears. An approximation to the $P_T$ versus $\delta S$ curve is a rectangle in which $P_T(\text{FAILURE})$ and $\delta SB$ are the distinguishing features. This is obviously a better approximation for the left gear than the right. $P_T(\text{FAILURE})$ is available from the records. The value of $\delta SB$ and the damping constant were determined by trial. The curves that were used in the final correlation are shown in Figure 37.

Resistance to Forward Motion in Soft Soil

The total resistance to forward motion occurring at the contact area of the tire with the ground is considered to be made up of sliding and rolling friction, where sliding friction is defined as that which causes the wheel to accelerate its rotational motion about the axle, and rolling friction is the remainder. During a landing on concrete, the rolling friction is almost small enough to be neglected; the sliding friction coefficient is large, approaching a value of 1.0 at certain values of slip ratio. In contrast, a landing on soft soil produces a low sliding friction and a high rolling friction. The major portion of the rolling friction on soft soil is assumed to come from deformation of the soil.

The low sliding friction in the landing on sod makes the spin-up time longer than that for concrete. If the soil is soft, the higher rolling friction causes a total drag load which is high and apparently inconsistent with the spin-up time, and the springback is diminished or eliminated.

For the 18 July landing on sod, adequate correlation between calculated and measured loads was obtained by using a maximum sliding coefficient of friction of 0.3 and a rolling coefficient of 0.2. All evidence pointed to the fact that soil deformation in this landing remained elastic and was small. For the 3 August landing, the soil deformation was calculated by the computing program as described earlier, and the rolling resistance...
was related to this deformation as described in the following paragraphs.

Assume that a wheel-mass-shock strut system with vertical velocity only is dropped on soft soil, as shown in Figure 38a. At any instant of time after gear contact, the tire will have penetrated the soil a distance \( \delta_S \).
The kinetic energy loss of the mechanical system up to that point will have been absorbed partly by deflection of the shock strut damper, partly by the tire deflection, and partly by the soil. Now assume that the wheel is moved forward a distance \( \Delta X \). The soil energy as represented by the deflection of the soil springs in the shaded area (Figure 38b) is

\[
E_S = K \cdot p \cdot A \cdot \delta_S
\]  

where
- \( K \) = a proportionality constant
- \( p \) = the pressure at the tire-soil interface
- \( A = \Delta X \cdot w \) = the planform area of the rut formed during horizontal motion
- \( w \) = trough width

The horizontal kinetic energy subtracted from the moving vehicle, resulting from the aft force imposed on the wheel by the soil, is

\[
E_A = D \cdot \Delta X
\]

where \( D \) = the resistance to forward motion.

Equating these energies and substituting for \( A \),

\[
D \cdot \Delta X = K \cdot p \cdot w \cdot \Delta X \cdot \delta_S
\]

\[
D = K \cdot p \cdot w \cdot \delta_S
\]

Thus, the drag load on the gear is proportional to the footprint pressure and the frontal area of the trough.

The soil springs are actually springs, masses, and dampers. However, under dynamic loads, the masses and dampers produce a nonlinear force deflection curve. In terms of the quasi-static approach, the value of \( K \) will vary between 0.5 and 1.0 and, within this range, will be a function of \( \delta_S \). For these purposes, \( K \) will be assumed to have one value up to the point of tire bottoming and another value above the bottoming, thus approximating a nonlinear curve by two straight lines. It must also be
assumed that the forward velocity does not change appreciably during the period under investigation.

Below the tire-bottoming load, $p$ is approximately constant and $w$ varies as $P_T^{1/2}$. Therefore,

$$D = K \sqrt{P_T} \cdot \delta_S \quad \text{below tire bottoming} \quad (12)$$

Above tire bottoming, $w$ can be assumed constant, and

$$p = p_o + \frac{P_T - P_{TB}}{A} \quad \text{(see page 56)} \quad (13)$$

so that

$$D \approx K_1 \cdot p_o + K_2 (P_{TB} - P_T) \delta_S$$

$$= D_B + K_3 (P_{TB} - P_T) \delta_S \quad \text{above tire bottoming} \quad (14)$$

where $D_B$ = the drag which exists as the time of tirebottoming.

Values of ground coefficient of friction derived from test data are presented in Figure 39.

ROUGH-TERRAIN LANDINGS AND ROLLOUTS

The calculated loads obtained from the 8-foot-per-second landings and rollouts on rough portions of the Franklin and Camp Pickett sites are shown in Figures 40 through 44. The gear loads for the landing at the Franklin site are relatively moderate after the landing impact. Those for the Camp Pickett site are severe and are sufficient to cause failure of the nose gear during the rollout phase. During landing impact, bumps increased the maximum vertical load on the Franklin field landing from 12,000 to 14,000 pounds and on the Camp Pickett field landing from 12,000 to 32,500 pounds over that calculated for the 18 July landing, which was on a relatively smooth portion of the Franklin field.
Since the maximum permissible vertical load on the main gear is 37,000 pounds, it is evident that failure would have occurred at the Camp Pickett site during landing impact at 8 feet per second if the bump load shown in Figure 40 at t = 0.11 had occurred 0.05 second earlier, at which time it would have been superimposed on the load resulting from impact.

The gears were off the ground during a substantial portion of the Camp Pickett rollout. It appears that bouncing is unavoidable on a terrain as rough as this one.

Based on these calculations, it is concluded that the airplane has sufficient strength for a field with a roughness spectrum equal to or less than that of the Franklin field site. However, similar calculations for other airplanes have shown that there is a critical airplane speed for crossing ground roughness and that calculations should be made at other speeds before judgment is passed. The critical speed depends upon the natural frequency of the airplane in pitch and heave (while on the ground) and the frequency content of the ground roughness.

Ground roughness of the nature of the Camp Pickett site is too severe for the airplane as currently designed.
Figure 19. Comparison of Measured and Calculated Strut Loads for the 2 August Landing.
Figure 20. Calculated Ground Loads for the 2 August Landing.
Figure 21. Calculated Strut Air and Oil Pressures for the 2 August Landing.
Figure 22. Calculated and Measured Strut Pressures for the 2 August Landing.
Figure 23. Calculated CG Acceleration for the 2 August Landing.
Figure 24. Comparison of Measured and Calculated Strut Loads for the 18 July Landing.
Figure 25. Calculated Ground Loads for the 18 July Landing.
Figure 26. Calculated and Measured Strut Pressures for the 18 July Landing.
Figure 27. Calculated CG Accelerations During the 18 July Landing.
Figure 28. Comparison of Measured and Calculated Strut Loads for the 3 August Landing.
Figure 29. Calculated Ground Loads for the 3 August Landing.
Figure 30. Calculated Strut Air and Oil Pressures for the 3 August Landing.
Figure 31. Calculated and Measured Strut Pressures for the 3 August Landing.
Figure 32. Calculated CG Accelerations for the 3 August Landing.
Figure 33. Ground Elevation Encountered by Main Gear as a Function of Time After Touchdown for Rough Field Landings and Rollouts.
Figure 34. Stress-Strain Curves for a Soil in Compression.
NOTES: 1. MAIN GEAR TIRE SIZE:
   10 PLY 8.50 x 10
2. INFLATION PRESS = 80 PSI

Figure 35. Soil Pressure Versus Tire Load.

Figure 36. Tire and Soil Load-Deflection Relationships.
Figure 37. Assumed Relationship Between Tire Load and Soil Deflection.
Figure 38. Mechanical Analogy for Development of Rolling Resistance in Soft Soil.
Figure 39. Total Ground Coefficients of Friction Derived From Test Data.

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Figure 40. Calculated Main Gear Vertical Strut Loads for Landings and Rollouts on Rough Terrain.
Figure 41. Calculated Main Gear Strut Drag Loads for Landings and Rollouts on Rough Terrain.
Figure 42. Calculated Nose Gear Vertical Loads for Landings and Rollouts on Rough Terrain.
Figure 43. Calculated Nose Gear Strut Drag Loads for Landings and Rollouts on Rough Terrain.
Figure 44. Rigid Body CG Accelerations for Landings and Rollouts on Rough Fields.
COMPARISON OF CALCULATED AND MEASURED LOADS

2 August Landing (see Figures 19 through 23)

For the 2 August landing on concrete, the complexities induced by soil contour and deflection were not present. The behavior of the right gear has been discussed previously, and the correlation shown in Figure 6 is obtained by assuming that not all of the oil had returned below the orifice at the time of touchdown. The general shape of the vertical load curve and several details are similar. With more effort, it is believed that the correlation could have been improved greatly; however, the additional effort was not considered to be worthwhile in view of the untypical gear condition.

The drag load on the right gear was predicted reasonably well; however, there was a secondary frequency in this record and in the drag record of the left gear that was not predicted and that contributed to inaccuracy. The second mode is believed to come from torsion of the fork, since the fork is not symmetrical, but extensive efforts to include this motion did not produce the desired results.

Peak vertical loads on the left main gear and the nose gear and the drag load on the nose gear were predicted well.

18 July Landing (see Figures 24 through 27)

These loads were calculated on the basis that the ground was hard and smooth. Thus, a $\mu_S = 0.3$ and a $\mu_R = 0.2$ were used, but no soil deflection was computed. No permanent set or rutting of the soil was evident after this landing.

The right main gear peak load and the drag load were predicted with good accuracy. The secondary mode mentioned above did not appear in the right gear drag but did appear in the left.

The shape of the calculated vertical load curves does not agree well with the shape of the measured vertical load curves. It is believed that a significant portion of the discrepancy can be attributed to the terrain contour, which was not included and could not be included in the calculations.

The only test data available for the nose gear was the point of touchdown, which the calculations predicted satisfactorily. The nose gear loads are insignificant. The lack of test data probably resulted from insufficient amplitude (gain) on the nose gear load channels.
3 August Landing (see Figures 28 through 32)

The correlation between the calculated and measured left main gear loads shown in Figures 28 and 30 is remarkable in view of the complexities involved. The correlation for the right main gear was not nearly as successful, especially for the drag load. Lack of agreement on the right gear is considered to be caused by one or more of the following:

1. The right gear may have been operating in a nonstandard manner as in the 2 August landing (see page 55).

2. The model of the soil may be inadequate for landings in which the tire load far exceeds the bottoming load.

3. The rolling coefficient of friction of a tire that has far exceeded its bottoming load may be substantially greater than that for an unbottomed tire.

There are insufficient data to determine the exact cause of the discrepancy; however, work done in connection with the TA-4F airplane (Reference 5) lends support to the view that high rolling coefficients will be obtained for a tire that is subjected to a load far in excess of the bottoming load, even on concrete. In the present problem, the tire bottoms at about 20,000 pounds, and the load stays above this figure from t = 0.04 to 0.20. The left gear also exceeds the bottoming load, but only by a small amount.

The calculated nose gear loads are shown in Figure 28. The sudden drop in vertical load at t = 0.07 second is the simulated failure. The vertical nose gear loads measured in drop tests at 19.6 feet per second (Reference 6) are superimposed on Figure 29. The drop-test results confirm the extremely rapid rise in vertical load with time which was predicted by the computer.

Figure 45 shows the calculated strength diagram of the nose gear for strokes of 3 inches and 9 inches. With a stroke of 9 inches, the outer cylinder is more critical than the piston until a vertical load of more than 27,000 pounds is applied. At 3 inches of stroke, the piston is critical. The piston strength, together with the calculated loads, is replotted on Figure 46. This figure indicates that failing loads were applied at S = 2.0 inches. This is not consistent with the location of the fracture, which was at a position corresponding to a stroke of 9 inches. It is surmised that a small finite amount of time was required for the loads experienced at S ≥ 2 to produce deflections corresponding to failure.
and that during that time, the gear continued to stroke. It should be re-
membered that the strength diagram is a static strength diagram, and 
the deflections incorporated therein correspond to slowly applied loads.

Figure 45. Calculated Nose Gear Strength Diagram.
Figure 46. Calculated Nose Gear Piston Strength Diagram Showing Calculated Loads Experienced During 3 August Landing.
CONCLUSIONS

The dynamic loads computing program used in this investigation was able to predict the gear loads from flight-test landings with about the same accuracy demonstrated in an earlier investigation involving loads from moving drop tests (Reference 3). This accuracy is estimated to be within ±10 percent for the peak loads. Many, but not all, of the peculiarities of the shapes of the individual load curves were duplicated.

The differences between test and calculated loads illustrated herein are not all attributable to errors or inappropriate assumptions in the mathematical representation of the airplane. Differences also result from instrumentation errors, effects of ground roughness, and lack of precise knowledge regarding the initial conditions. The ability to obtain the noted accuracy with a test vehicle subjected to aerodynamic forces and having 6 degrees of freedom represents a considerable advancement over the previously used 2-degree-of-freedom procedures.

It is believed that the greater part of any errors attributable to the computing program still lies in the detailed dynamic representation of the gears and in the duplication of the ground-tire interaction. More precise knowledge of the internal bearing friction, the variation of orifice coefficients with Reynolds number, and the polytropic compression exponent for nitrogen is needed. Although a satisfactory correlation was made in the 3 August landing by assuming a soil load-deflection relationship, basic soil data and a theory from which such load-deflection relationships can be derived need to be developed.

Much remains to be done in the area of side load prediction and measurement. While the mathematical statement of the torsional motion of the strut and the ground-tire reaction to yaw has been well developed, experimental verification of the accuracy of the representation is restricted by difficulties encountered in the measurement of side loads. These difficulties arise from the fact that high vertical loads and strut bending and torsional deflections combine to induce side load components of appreciable magnitude. Because of the importance of deflections, a static calibration gives, at best, a first approximation of the loads existing in the dynamic situation. No satisfactory procedure has been developed to provide a dynamic calibration for side loads.
The calculations predicted a failure of the nose gear on the 3 August landing. While the calculated stroke at failure appears to be inconsistent with the observed facts, this is not a matter of great significance.

The maximum total ground coefficient of friction measured on the main gears during the 3 August landing was 0.85. It is believed that the use of a rolling coefficient of 0.85 in the design of the nose gear would have been sufficient to prevent failure. In Reference 2, a maximum rolling coefficient of 1.0 is recommended for design. In light of the present test results, the recommended value of 1.0 seems to be correct if it is intended that strength be incorporated for the case in which soil failure occurs. Otherwise, the value would be excessively conservative.

The 3 August landing was successfully simulated on the computer by applying some approximate relationships describing the tire-soil interaction. The analysis provided an explanation for the disastrous results of the 3 August landing and emphasized the dangers of exceeding the tire-bottoming load when landing on soft soil.

The computed loads developed in this study from landings and rollouts on rough terrain gave a measure of what constitutes "rough" terrain as far as the OV-1 airplane is concerned. The Camp Pickett site contained roughness that was in excess of the OV-1 gears' strength capabilities. The Franklin field roughness appeared to be within the gears' capabilities.
RECOMMENDATIONS

In order to calculate the dynamic loads more accurately, knowledge of the following fundamental interior gear phenomena and parameters is needed: (1) the bearing friction at high contact pressures, (2) the value of the polytropic exponent for nitrogen compression at different compressive speeds, (3) the effects on gear characteristics of the dissolving and mixing of nitrogen in oil, and (4) the orifice coefficients as a function of orifice shape and Reynolds number. While values for these parameters are known for average conditions, they are not adequately established for extreme conditions such as were encountered in the 19-foot-per-second landing investigated herein or in design drops for carrier-based aircraft. Therefore, it is recommended that research be conducted to obtain the necessary information.

The rolling coefficient of friction for fully compressed tires is not known and should be determined if calculations are to be made for limiting conditions.

The soil model used herein for correlation with the 3 August landing probably does not have general applicability because it has been oversimplified. It is recommended that further work be done to improve the soil model and to provide basic soil data necessary for application of the model in dynamic calculations.

It is recommended that rolling drop tests be conducted during which the OV-1 gear, or a similar gear, is dropped on soils of varying degrees of softness, and that attempts be made to compute the loads by means of a dynamic loads program that incorporates a soil model. It is also recommended that this same test program be extended to measure the loads developed on the gear when it traverses terrain with random roughness and that these loads be compared to computed loads.

It is recommended that mathematical models be made for several gear concepts having strong rough-terrain capability and that these gears be landed and taxied mathematically on typical rough terrain to determine their relative tolerance to ground roughness. On the basis of these results, it is recommended that a gear be built which incorporates the features of the best rough-terrain gear model, and that this gear be proved by rolling drop tests on soft soil and over rough contours.
LITERATURE CITED


*Now Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory.
# APPENDIX I
## EQUATIONS OF MOTION

### LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>THEORY</th>
<th>FORTRAN</th>
<th>DESCRIPTION</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A</td>
<td>pitch attitude of airplane</td>
<td>rad</td>
</tr>
<tr>
<td>a</td>
<td>AA</td>
<td>vertical motion of unsprung mass, measured along strut center line</td>
<td>in., sec.</td>
</tr>
<tr>
<td>A_{BRG}</td>
<td>ABRG</td>
<td>vertical distance from lower bearing to the unsprung mass when the strut is fully extended, measured along strut center line</td>
<td>in.</td>
</tr>
<tr>
<td>A_D</td>
<td>ADRAG</td>
<td>aerodynamic drag force at aerodynamic center</td>
<td>lb</td>
</tr>
<tr>
<td>{AIR}</td>
<td></td>
<td>column matrix of aerodynamic forces</td>
<td></td>
</tr>
<tr>
<td>AIR_\alpha</td>
<td></td>
<td>pitching aerodynamic moment about the airplane cg</td>
<td>lb-in.</td>
</tr>
<tr>
<td>AIR_\theta</td>
<td></td>
<td>rolling aerodynamic moment about the airplane cg</td>
<td>lb-in.</td>
</tr>
<tr>
<td>AIR_f</td>
<td></td>
<td>longitudinal aerodynamic forces in airplane body axis system</td>
<td>lb</td>
</tr>
<tr>
<td>AIR_h</td>
<td></td>
<td>vertical aerodynamic force in airplane body axis system</td>
<td>lb</td>
</tr>
<tr>
<td>A_L</td>
<td>ALIFT</td>
<td>aerodynamic lift force at aerodynamic center</td>
<td>lb</td>
</tr>
<tr>
<td>A_\alpha</td>
<td>APITCH</td>
<td>aerodynamic pitching moment about the aerodynamic center</td>
<td>lb-in.</td>
</tr>
<tr>
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<td>TEXT DESCRIPTION</td>
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<td>---------</td>
<td>---------</td>
<td>----------------------------------------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>( A_{nn} )</td>
<td>ANN</td>
<td>annular distance between the metering pin and the orifice</td>
<td>in.</td>
</tr>
<tr>
<td>( A_p )</td>
<td>AP</td>
<td>sectional area of metering pin</td>
<td>in.(^2)</td>
</tr>
<tr>
<td>( A_{POD} )</td>
<td>APOD</td>
<td>sectional area of piston based on outside diameter at lower bearing</td>
<td>in.(^2)</td>
</tr>
<tr>
<td>( [AM] )</td>
<td></td>
<td>matrix of coefficients for calculating airplane accelerations from the aerodynamic forces</td>
<td>lb, in., sec</td>
</tr>
<tr>
<td>( A_R )</td>
<td>AR</td>
<td>sectional area of rebound chamber at the piston lower bearing</td>
<td>in.(^2)</td>
</tr>
<tr>
<td>( A_S )</td>
<td>AS</td>
<td>total cross-sectional area of rebound chamber orifices</td>
<td>in.(^2)</td>
</tr>
<tr>
<td>( A_{SPL} )</td>
<td>ASPL</td>
<td>sectional piston area at the upper bearing, including splines</td>
<td>in.(^2)</td>
</tr>
<tr>
<td>( [AT] )</td>
<td></td>
<td>matrix of coefficients for calculating airplane rigid body accelerations from gear forces</td>
<td>lb, in., sec</td>
</tr>
<tr>
<td>( A_1 )</td>
<td>A1</td>
<td>sectional area of gear oil chamber without reduction for metering pin</td>
<td>in.(^2)</td>
</tr>
<tr>
<td>( A_0 )</td>
<td>A0</td>
<td>orifice area without reduction for metering pin</td>
<td>in.(^2)</td>
</tr>
<tr>
<td>( B_W )</td>
<td>B</td>
<td>tire spring constant in side direction</td>
<td>lb/ft</td>
</tr>
<tr>
<td>( b )</td>
<td>BB</td>
<td>lateral motion of unsprung mass, measured perpendicular to strut center line</td>
<td>in., sec</td>
</tr>
<tr>
<td>THEORY</td>
<td>FORTRAN</td>
<td>UNIT</td>
<td></td>
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<td>--------</td>
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<td>------</td>
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</tr>
<tr>
<td>( \bar{b} )</td>
<td>BBAR</td>
<td>elastic motion of the unsprung mass relative to the gear attach point in the lateral direction, measured perpendicular to strut center line</td>
<td>in., sec</td>
</tr>
<tr>
<td>( B_{BRG} )</td>
<td>BBRG</td>
<td>vertical distance between upper and lower bearings when strut is fully extended, measured along strut center line</td>
<td>in.</td>
</tr>
<tr>
<td>( C )</td>
<td>CHORD</td>
<td>mean aerodynamic chord length of wing</td>
<td>in.</td>
</tr>
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<td>( \bar{C} )</td>
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<td>vertical ground forces, acting parallel to strut center line</td>
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<td>gear-induced rolling moment acting on the airplane</td>
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<tr>
<td>$W_U$</td>
<td>WU</td>
<td>lb</td>
<td></td>
</tr>
<tr>
<td>$X$</td>
<td>X</td>
<td>in.</td>
<td></td>
</tr>
<tr>
<td>$X_A$</td>
<td>XA</td>
<td>in.</td>
<td></td>
</tr>
<tr>
<td>$X_N$</td>
<td>XN</td>
<td>lb</td>
<td></td>
</tr>
<tr>
<td>$X_T$</td>
<td>XT</td>
<td>in.</td>
<td></td>
</tr>
</tbody>
</table>

volume in strut air chamber when strut is fully extended
velocity of the flow of hydraulic fluid through the strut orifice
wind velocity, measured parallel to the runway; + headwind
forward velocity of the airplane relative to the air, measured parallel to the runway
vertical velocity of the airplane, measured perpendicular to the runway
airplane weight
load factor, initial airplane acceleration = (1 - $W_L$) g
weight of unsprung mass
lateral distance from airplane cg to gear attach point, measured in airplane body axis system
lateral distance from gear attach point to cg of unsprung mass, measured in airplane body axis system
cornering power, parameter used in tire side force calculations
total distance wheel has traveled parallel to the runway after initial contact
<table>
<thead>
<tr>
<th>THEORY</th>
<th>FORTRAN</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>Y</td>
<td>in.</td>
</tr>
<tr>
<td>Y_A</td>
<td>YA</td>
<td>in.</td>
</tr>
<tr>
<td>Y_AC</td>
<td>YAC</td>
<td>in.</td>
</tr>
<tr>
<td>Y_CG</td>
<td>YCG</td>
<td>in.</td>
</tr>
<tr>
<td>Y_EM</td>
<td>YEM</td>
<td>in.</td>
</tr>
<tr>
<td>Z</td>
<td>Z</td>
<td>in.</td>
</tr>
<tr>
<td>Z_AC</td>
<td>ZAC</td>
<td>in.</td>
</tr>
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<td>Z_CG</td>
<td>ZCG</td>
<td>in.</td>
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<td>Z_EM</td>
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<td>in.</td>
</tr>
<tr>
<td>Z_G</td>
<td>ZG</td>
<td>in.</td>
</tr>
<tr>
<td>a</td>
<td>ALPHA</td>
<td>deg</td>
</tr>
<tr>
<td>β</td>
<td>BETA</td>
<td>rad, sec</td>
</tr>
<tr>
<td>δ_s</td>
<td>DEL, ANGS</td>
<td>rad</td>
</tr>
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<td><strong>THEORY</strong></td>
<td><strong>FORTRAN</strong></td>
<td><strong>UNIT</strong></td>
</tr>
<tr>
<td>------------</td>
<td>-------------</td>
<td>---------</td>
</tr>
<tr>
<td>$\theta$</td>
<td>THETA</td>
<td>roll motion of the airplane cg in airplane body axis system</td>
</tr>
<tr>
<td>$\mu_{B_1}$</td>
<td>SLMU</td>
<td>coefficient of bearing friction at the upper bearing</td>
</tr>
<tr>
<td>$\mu_{B_2}$</td>
<td>SLMU</td>
<td>coefficient of bearing friction at the lower bearing</td>
</tr>
<tr>
<td>$\mu$</td>
<td>MUBAR</td>
<td>tire coefficient of sliding friction in the longitudinal direction</td>
</tr>
<tr>
<td>$\mu_\beta$</td>
<td>SLBMU</td>
<td>coefficient of bearing friction at the strut splines</td>
</tr>
<tr>
<td>$\mu_\psi$</td>
<td>PSIMU</td>
<td>tire coefficient of sliding friction in the lateral direction</td>
</tr>
<tr>
<td>$\rho$</td>
<td>RHO</td>
<td>density of strut hydraulic fluid</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>SIGMA</td>
<td>roll angle the strut center line makes with the vertical axis of the airplane body axis system, + outboard</td>
</tr>
<tr>
<td>$\phi$</td>
<td>PHI</td>
<td>pitch angle the strut center line makes with the vertical axis of the airplane body axis system, + forward</td>
</tr>
<tr>
<td>$\psi_s$</td>
<td>PSIS</td>
<td>tire yaw angle</td>
</tr>
<tr>
<td>$\omega$</td>
<td>OMEGA</td>
<td>wheel rotation about the wheel axle</td>
</tr>
<tr>
<td>$\omega_0$</td>
<td>OMEGAO</td>
<td>wheel rotating rate about the wheel axle at time $= 0.0$</td>
</tr>
<tr>
<td>TABLE</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>BTAB</td>
<td>Table of spline bearing friction coefficients versus strut stroke</td>
<td></td>
</tr>
<tr>
<td>CDTAB</td>
<td>Table of oleo orifice coefficients of discharge versus a rate of fluid flow measured in in.$^2$/sec; argument used in this program is $(V_o)(A_{nn})$</td>
<td></td>
</tr>
<tr>
<td>CORTAB</td>
<td>Table of tire turning power versus tire deflection</td>
<td></td>
</tr>
<tr>
<td>CTTAB</td>
<td>Table of tire load versus tire deflection</td>
<td></td>
</tr>
<tr>
<td>GRTAB</td>
<td>Table of ground deflection and tire deflection plus ground deflection versus ground load</td>
<td></td>
</tr>
<tr>
<td>LOWTAB</td>
<td>Table of lower bearing friction coefficients versus strut stroke</td>
<td></td>
</tr>
<tr>
<td>QOTAB</td>
<td>Table of rebound chamber orifice coefficients of discharge versus strut stroke</td>
<td></td>
</tr>
<tr>
<td>SLIP</td>
<td>Table of ground sliding coefficients of friction versus slip ratio</td>
<td></td>
</tr>
<tr>
<td>UPTAB</td>
<td>Table of upper bearing friction coefficients versus strut stroke</td>
<td></td>
</tr>
<tr>
<td>XYTABL</td>
<td>Table of ground height versus distance down the runway</td>
<td></td>
</tr>
</tbody>
</table>
UNSPRUNG MASS EQUATIONS OF MOTION

Assumptions

1. No elastic rotation of the strut in the pitch direction
2. No nonlinear accelerations induced by wheel rotation
3. No elastic rotation of the strut in the roll direction

A. Before tire touches ground

\[
\begin{align*}
\ddot{a} &= \cos \sigma [\Sigma_1 \cos \phi + \Sigma_2 \sin \phi] \\
\dot{b} &= \Sigma_1 \cos \phi \sin \sigma + \cos \phi (Z_A \cos \sigma - X_A \sin \sigma) \Sigma_3 \\
\ddot{d} &= [-\Sigma_1 \sin \phi + \Sigma_2 \cos \phi - (Y_A \sin \phi - Z_A \cos \phi) \Sigma_4] \cos \sigma \\
\ddot{\beta} &= \frac{T_\beta + F_D E_B - F_B E_D}{I_\beta} \\
\dot{S} &= 0.0 \\
\dot{b} &= 0.0 \\
\dot{d} &= 0.0 \\
\dot{\omega} &= 0.0
\end{align*}
\]

B. After tire touches ground

\[
\begin{align*}
\ddot{a} &= \cos \sigma [\Sigma_1 \cos \phi + \Sigma_2 \sin \phi] \text{ (before strut moves)} \\
&= \left[(W_u - P_T) \cos (\phi + A) \cos \sigma + F_A - (\mu P_T + P_S \sin \beta) \sin (\phi + A) \cos \sigma \right. \\
&\left. - (\sin \sigma + \theta \cos \sigma \cos \phi) \cos \beta P_S + F_E \sin F \right] \frac{W_u}{g} \text{ (after strut moves)}
\end{align*}
\]

\[
\begin{pmatrix}
\ddot{\beta} \\
\dot{d} \\
\dot{b}
\end{pmatrix} =
\begin{pmatrix}
C_{11} & C_{12} & C_{13} \\
C_{21} & C_{22} & 0.0 \\
C_{31} & C_{32} & C_{33}
\end{pmatrix}^{-1}
\begin{pmatrix}
f_1 \\
f_2 \\
f_3
\end{pmatrix}
\]

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where

\[ C_{11} = I_\beta \]

\[ C_{12} = \left( (E_b + \bar{b}) \cos \beta - (E_d + \bar{d}) \sin \beta \right) \frac{W_u}{g} \]

\[ C_{21} = C_{12} \]

\[ C_{13} = -\left( (E_d + \bar{d}) \cos \beta + (E_b + \bar{b}) \sin \beta \right) \frac{W_u}{g} \]

\[ C_{31} = C_{13} \]

\[ C_{22} = \frac{W_u}{g} \]

\[ C_{33} = \frac{W_u}{g} \]

\[ f_1 = (E_b + \bar{b} + E_x) F_x - (E_d + \bar{d}) F_y + T_\beta \]

\[ f_2 = F_x + F_D \]

\[ f_3 = F_y + F_B \]

\[ \ddot{\bar{b}} = \bar{b} - \Sigma_1 \cos \phi \sin \]

\[ \ddot{\bar{d}} = \dot{\bar{d}} + \cos \sigma \left[ \Sigma_1 \sin \phi - \Sigma_2 \cos \phi - (E_L - S) \Sigma_4 \right] \]

\[ \ddot{\omega} = \frac{\left( \mu P_T - P_S \sin \beta \right) (R_T - C_T)}{E_R I_R} \]

where \( \Sigma_1, \Sigma_2, \Sigma_3, \) and \( \Sigma_4 \) are the vertical, fore and aft, roll, and pitch accelerations of the airplane at the strut attach point respectively.
GROUND FORCES

Assumptions

Small airplane roll attitude

\[
F_x = -(\mu P_T + P_S \sin \beta) \cos (\phi + A) + P_T \sin (\phi + A)
\]

\[
F_y = -(\mu P_T + P_S \sin \beta) (\sin \sigma \sin (\phi + A) + \theta \sin \sigma \cos \sigma) + P_S \cos \sigma \cos \beta - P_T (\cos (\phi + A) \sin \sigma + \theta \cos \sigma \cos \beta)
\]

\[
F_z = (W_u - P_T) \cos (\phi + A) \cos \sigma - (\mu P_T + P_S \sin \beta) \sin (\phi + A) \cos \sigma - P_S \cos \beta (\sin \sigma + \theta \cos \sigma \cos \phi)
\]

TIRE FORCES

Assumptions

1. No restoring torque in tire
2. No bearing friction in wheel assembly
3. No tire inertia effects
4. No tire hysteresis effects
5. Centrifugal forces have no effect on tire vertical deflection
6. Constant side coefficient of friction

A. Tire deflection

\[
C_T = R_T \cos \sigma - D + Z_G
\]

\[
D = D_{CG} - (Z_D \cos \theta + X_D \sin \theta) \cos A + Y_D \sin A + G_\delta
\]

\[
Z_D = Z + (E_L - S) \cos \phi \cos \sigma - \{d + E_D \cos \beta + (E_B + E_X) \sin \beta\} \sin \phi + L_{FORK} \cos (F - \phi) + e \sin (F - \phi) + S_{TDF} - \delta_S E_B \cos \phi
\]

\[
X_D = X + (E_L - S) \cos \phi \sin \sigma + \{b - E_D \sin \beta + (E_B + E_X) \cos \beta\} \cos \sigma - E_D \delta_S \cos \phi \sin \sigma
\]
\[ Y_D = Y + (E_L - S) \sin \phi \cos \sigma + \{ \tilde{d} + E_D \cos \beta + (E_B + E_X) \sin \beta \} \cos \phi \]

\[ + e \cos (F - \phi) - \delta_s E_B \sin \phi \cos \sigma \]

\[ \ddot{G}_\delta = \frac{p_T - C_G \left[ \dot{G}_\delta + \frac{12 V_E G_\delta}{XX1} \right] - XX1}{G_M} \]

\[ XX1 = \sqrt{R_T^2 - (R_T - C_T - G_\delta)^2} \]

\[ S_{TDF} = \frac{m}{j} \sum TH_j Q_j \]

B. Slip ratio

\[ SR = \left[ \frac{12 V_E - \frac{R_T - C_T}{E_R} \dot{\omega} + \dot{d} \cos (\sigma + \theta) \cos (\phi + \alpha)}{12 V_E - R_T \dot{\omega}_o} + A \left( E_L - S + R_T - \frac{C_T}{E_R} \right) \cos \sigma + E_B \dot{\beta} \cos (\sigma + \theta) \cos (\phi + \alpha) \right] \]

C. Vertical and drag forces

1. Smooth rigid ground

\[ F_T = \text{linear interpolation of CTTAB table using } C_T \text{ (tire deflection) as argument} \]

\[ XX2 = 0.0 \]

2. Flexible ground

\[ F_T = \text{linear interpolation of GRTAB table using } C_T \text{ (tire deflection) as argument and determining ground load} \]

\[ D_{EL} = \text{linear interpolation of GRTAB table using } C_T \text{ (tire deflection) as argument and determining ground plus tire deflection} \]
Equation for calculating ground load-deflection

\[
\delta_G = \frac{\log \left( \frac{P_{ult}}{P_{ult} - F_{KZ1}} \right)}{C_{DEL}}
\]

\( F_{KZ1} \) = value of tire load from CTTAB table

3. Rough terrain (see Figure 47)

\[
\delta_i = R_T - \sqrt{(U_K - X_i)^2 + (D_K - Y_i)^2}
\]

where \( i = 1 \ldots 5 \)

\( D_{EFL} = \delta_i \theta_0 / 5 \)

\( F_i = \) linear interpolation of CTTAB table using \( D_{EFL} \) as argument

\[
F_T = \sum_{i=1}^{5} F_i \cos \gamma_i
\]

\[
XX2 = -\sum_{i=1}^{5} F_i \sin \gamma_i
\]

4. \( P_T \) and \( \mu P_T \)

\[
P_T = F_T \cos \epsilon - P_D \sin \epsilon
\]

\[
\mu P_T = F_T \sin \epsilon + P_D \cos \epsilon
\]

\[
P_D = \mu F_T + XX2 + D_{RAG}
\]

\[
D_{RAG} = V_D G_\delta \sqrt{F_T} \quad \text{if} \quad P_{TB} \geq F_T
\]

\[
= V_D R_{PTB} + (F_T - P_{TB}) G_\delta D_{BTM} \quad \text{if} \quad P_{TB} < F_T
\]
D. Lateral force

\[ P_S = \left[ \frac{SR \psi_s}{|\psi_s|} + \left( \Phi - 0.14815 \Phi^3 \right) (1 - SR) \right] \mu_\psi P_T \left( 1 - e^{-BX_T} \right) \]

\[ \psi_s = \tan^{-1} \left[ \frac{\dot{b} - (R_T - C_T) \dot{\delta}_s}{|12 V_E + \ddot{d}|} \right] - \beta \]

\[ \eta = \frac{X_N \psi_s}{\mu_\psi P_T} \]

\[ \Phi = \begin{cases} 
1.5 & \text{for } |\eta| \geq 1.5 \\
\eta & \text{otherwise} 
\end{cases} \]

\[ X_M = \text{linear interpolation of CORTAB table using } C_T \text{ (tire deflection) as argument} \]

\[ B = \left[ \frac{SR \sin \psi_s}{1 - SR} \frac{\psi_s}{1.57} \right] \frac{B_H}{\mu_\psi P_T} \]

\[ X_T = \sqrt{\frac{[\dot{b} + (R_T - C_T) \dot{\delta}_s]^2 + [\ddot{d} + U_{CG} - U_{CG0}]^2}{12}} \]

### STRUT INTERNAL FORCES

**Assumptions**

1. Incompressible oil flow through one orifice
2. Constant torsional stiffness
3. Air compression in strut obeys general form of equation of state, \( PV^n = \text{const} \)
4. No damping of side bending moment
5. Sea level atmospheric pressure
A. **Vertical force**

\[ F_A = P_A + P_O + P_F \]

\[ P_O = \frac{\rho (A_1 - A_p)^3 \hat{\dot{S}} \hat{\dot{S}}}{2 C_D^2 (A_O - A_p)^2} \]

\[ C_D = \text{interpolation of CDTAB table using } V_0 A_{nn} \text{ as argument} \]

\[ V_O = \frac{A_1 S}{A_O - A_p} \]

\[ A_{nn} = \frac{\sqrt{A_O} - \sqrt{A_p}}{2} \]

1. **No rebound chamber**

\[ P_A = (P_E + 14.7 A_{POD}) \frac{V_{EA}}{(V_{EA} - S A_{POD})^{n_1}} - 14.7 A_{POD} \]

2. **Rebound chamber**

\[ P_A = \left[ \frac{P_E + 14.7 A_{POD}}{(1 + C_X)^n} - 14.7 A_{POD} \right] C_K \]

a. **Rebound chamber not filled with oil** \( E_O \leq A_R S \)

\[ n = n_1 \]

\[ C_K = \frac{A_{SPL}}{A_{POD}} \]
\[ C_X = \frac{(A_{SP} - S - E_Q)}{V_{EA}} + \frac{C_{Exp}(P_A - P_E)}{V_{EA} \cdot A_{POD}} \]

\[ E_Q = \frac{2}{\rho A_{SP} \cdot V_{EA}} \int_0^t Q_x \sqrt{P_A} \, dt \] (volume of oil in rebound chamber)

\[ Q_o = \text{interpolation of QOTAB table using S (stroke) as the argument} \]

b. Rebound chamber filled \( E_Q > A_R S \)

\[ n = n_2 \]

\[ C_K = 1.0 \]

\[ C_X = \frac{(A_{SP} - A_R) S + C_{Exp} \cdot \frac{P_A - P_E}{A_{POD}}}{V_{EA}} \]

\[ P_F = \mu_B F_{1TOT} + \mu_{B2} F_{2TOT} + \mu_F^E \cdot \text{TORQ} \]

\[ F_{1TOT} = \sqrt{F_1^2 + F_{1S}^2} \]

\[ F_1 = \left[ F_D (A_{BRG} - S) + L_{FORK} F_E + e (F_{AXD} \sin F - F_{AXS} \cos F) - F_A (E_D \cos \beta + E_B \sin \beta + \tilde{a}) \right] + \left[ B_{BRG} + S \right] \]

\[ F_{1S} = \left[ F_B (A_{BRG} - S) + F_L \cos \beta - F_A (\tilde{b} - E_D \sin \beta) \right] + \left[ B_{BRG} + S \right] \]

\[ F_{AXD} = F_D \cos \beta - F_B \sin \beta + \frac{T_\beta}{F_B} \]

\[ F_{AXS} = F_D \sin \beta + F_B \cos \beta - \frac{T_\beta}{F_B} \]

\[ F_{2TOT} = \sqrt{F_2^2 + F_{2S}^2} \]
\[ F_2 = F_1 + F_D \]
\[ F_{2S} = F_{1S} + F_B \]
\[ F_{\text{TORQ}} = \frac{T_\beta}{R_S} \]
\[ \mu_{B1} = \text{interpolation of UPTAB table using } S \text{ as argument} \]
\[ \mu_{B2} = \text{interpolation of LOWTAB table using } S \text{ as argument} \]
\[ \mu_\beta = \text{interpolation of BTAB table using } S \text{ as argument} \]

B. Drag force
\[ F_D = - (\ddot{d} - D_{FA} - E_X \beta) \left( K_{32} + S K_{33} \right) - \bar{C} (\ddot{d} - E_X \dot{\beta}) \]
\[ D_{FA} = F_A K_1 (E_D - L_{\text{FORK}} \sin F + e \cos F) \]

C. Side force
\[ F_B = - (\ddot{b} + K_4 F_A) \left( K_{22} + S K_{23} \right) - C_S \dot{b} \]

D. Torsional moment
\[ T_\beta = - K_\beta \beta - C_\beta \dot{\beta} \]

E. Force in fork
\[ F_E = -(K_E + S D_{\text{AMP}}) e - C_F \dot{e} \]
AIRPLANE EQUATIONS OF MOTION (see Figure 48)

Assumptions

1. No airplane yaw
2. No airplane lateral motion
3. Maximum number of flexible modes is 10
4. Modal accelerations due to gravity and modal accelerations due to aerodynamic forces are neglected

\[
\{\ddot{Q}\} = \begin{bmatrix} \{\ddot{R}\} \\ \{\ddot{\theta}\} \\ \{\ddot{f}\} \\ \{\ddot{q}\} \end{bmatrix} = \begin{bmatrix} \dot{h} \\ \dot{A} \\ \dot{\theta} \\ \dot{f} \end{bmatrix}
\]

All motions are in airplane body axis system

\( h \) = Rigid body vertical motion
\( A \) = Rigid body pitch
\( \theta \) = Rigid body roll
\( f \) = Rigid body longitudinal motion
\( q \) = Flexible modes of airplane

\[
\{\ddot{R}\} = [AT] \{F\} + [AM] \{AIR\} + \begin{bmatrix} g \cos A \\ 0 \\ 0 \end{bmatrix}
\]

\[
\{\ddot{q}\} = [DQ] \{\ddot{q}\} + [SQ] \{q\} + [QT] \{F\}
\]
Gear forces

\[
\{F\} = \begin{bmatrix}
F_h \\
F_a \\
F_\theta \\
F_f
\end{bmatrix}
\]

\[
F_h = -F_A \cos \sigma \cos \phi + F_D \cos \sigma \sin \phi + F_B \sin \sigma \cos \phi
\]

\[
F_a = -F_D \cos \sigma (E_L - S)
\]

\[
F_\theta = -F_B (E_L - S)
\]

\[
F_f = -F_A \cos \sigma \sin \phi - F_D \cos \sigma \cos \phi + F_B \sin \sigma \sin \phi
\]

Aerodynamic forces

Assumptions

1. Variable airspeed
2. No yaw or lateral motion
3. Sea level altitude
4. Steady air flow
5. \(C_{Lq}, C_{L\alpha}\) and \(C_{M\alpha}\) are zero

\[
\{\text{AIR}\} = \begin{bmatrix}
\text{AIR}_h \\
\text{AIR}_\alpha \\
\text{AIR}_\theta \\
\text{AIR}_f
\end{bmatrix}
\]
AIR\(_h\) = \(-A_L \cos \alpha - A_D \sin \alpha - T \sin \Omega_T\)

AIR\(_\alpha\) = \(A_\alpha + A_L \bar{Y}_{AC} - A_D Z_{AC} + T (\bar{Y}_{EM} \sin \Omega_T + \bar{Z}_{EM} \cos \Omega_T)\)

AIR\(_\theta\) = \(Z_z \ C \ C_{MR} \ \dot{\theta}\)

AIR\(_f\) = \(A_L \sin \alpha - A_D \cos \alpha + T \cos \Omega_T\)

\(A_L = Z_z \left(C_{LB} + C_{LiH} |\dot{H}| + C_{Li} \delta_{E}\right)\)

\(A_\alpha = Z_z \ C \left(C_{MB} + C_{MiH} |\dot{H}| + C_{Mi} \delta_{E} + \frac{C_{Mq} \ \dot{A} \ C}{24.0 \ V_E}\right)\)

\(A_D = Z_z \left(C_{DB} + C_{DiH} |\dot{H}| + C_{Di} \delta_{E}\right)\)

\(Z_z = \frac{S_W}{842} \left[ V_z^2 + (V_E + V_W)^2 \right] \)

\(\alpha = A + \gamma\)

\(\gamma = \tan^{-1} \left(\frac{V_z}{V_y}\right)\)

\(\bar{Y}_{AC} = Y_{CG} - Y_{AC}\)

\(\bar{Z}_{AC} = Z_{CG} - Z_{AC}\)

\(\bar{Y}_{EM} = Y_{CG} - Y_{EM}\)

\(\bar{Z}_{EM} = Z_{CG} - Z_{EM}\)
Figure 47. Geometry for Rough-Terrain Tire.
Figure 48. Sign Convention for Equations of Motion.
POSITIVE DIRECTION OF PARAMETERS IS ILLUSTRATED IN SKETCHES.

Figure 48. Continued.
POSITIVE DIRECTION OF PARAMETERS IS ILLUSTRATED IN SKETCHES

Figure 48. Continued.
POSITIVE DIRECTION OF PARAMETERS IS ILLUSTRATED IN SKETCHES

**MAIN GEAR**

\[ \begin{align*}
F_A & \quad F_D \\
\mu_t P_t & \quad P_t \\
\text{FWD} & \quad \text{OUTBD}
\end{align*} \]

**NOSE GEAR**

\[ \begin{align*}
T_B & \quad F_D \\
\mu_t P_t & \\
\text{FWD} & \quad \text{OUTBD}
\end{align*} \]

Figure 48. Continued.
POSITIVE DIRECTION OF PARAMETERS IS ILLUSTRATED IN SKETCHES.

Figure 48. Concluded.
APPENDIX II
TEST REPORT
ON
POWER SPECTRAL DENSITY COMPARISONS OF TWO UNIMPROVED
DIRT SURFACE RUNWAYS SELECTED BY THE ARMY FOR USE IN
A DYNAMIC TAXI ANALYSIS PROGRAM

PURPOSE

The purposes of the report are to present the power spectral density
(PSD) characteristics of two unimproved dirt runways and to compare
these characteristics with available Air Force data on selected types
of airfields. The two unimproved dirt runways are located at Franklin,
Virginia (run number 05), and Camp Pickett, Virginia (run number 1A).

FACTUAL DATA

1. The United States Army Aviation Materiel Laboratories
    (USAAVLABS), Fort Eustis, Virginia, is jointly conducting
dynamic taxi tests with the McDonnell-Douglas Corporation,
Douglas Aircraft Company. An instrumented YOV-1A
Mohawk is being used as the test aircraft. Six unimproved
dirt fields were established as test sites.

2. Profile elevation data were gathered from the selected
unimproved runways by USAAVLABS using a profilometer
that sampled surface elevations every 1/2 foot. The length
of each line of survey was 500 feet.

3. The data were to be used as a runway forcing function in a
dynamic taxi analysis program. Results obtained theoretically
are to be correlated with those results obtained from taxi tests
on unimproved runway surfaces.

4. The U.S. Army Aviation Materiel Laboratories requested AF
Flight Dynamics Laboratory (FDDs) to reduce the profile data
gathered into profile and power spectral density curves. This
request resulted from an initial request by Douglas Aircraft
Company to have the data reduced into the same PSD form that
the Air Force uses for similar programs.
FDDS DATA REDUCTION PROGRAM

Profile data have been reduced to power spectral density for the center line of two of the six sites from which profile data were gathered. The profile data were reduced to PSD form with a 7044-7094 direct coupled digital computer using a previously established program based on equations presented in Reference 7. Data conditioning (jumps due to setups, bad data points, etc.) is included in the program. This method incorporated the removal of the linear trend. To obtain a profile curve relative to a zero reference, the value of the first data point has been subtracted from each data point.

RESULTS

A comparison (Figure 49) of the PSD for the Franklin, Virginia, and Camp Pickett, Virginia, sites with the PSD for a multi-matted surface runway (curves obtained from Reference 8) shows that the power levels for both sites are above the multi-matted runway power level for all reduced frequencies.

The Franklin site has power factors ranging between 1.5 times and 3 times the power level of the multi-matted surface for a wavelength of 3.5 feet to 18 feet. This wavelength range was determined to be most important for the YOV-1A airplane. The Camp Pickett site has a power factor which is about 6 times the power level of the Franklin site for a wavelength range of 3.5 feet to 18 feet.

A comparison of the PSD of the above two sites was made with current Air Force unimproved airfield PSD data. The results show that both the Franklin and Camp Pickett, Virginia, sites are generally within the power band levels of the current Air Force data.
Figure 49. Landing Surface Power Spectral Density Comparisons.
APPENDIX III
SCHEMATIC OF INSTRUMENTATION CIRCUITRY

Figure 50. Schematic of Instrumentation Circuitry.
APPENDIX IV
RADAR VELOCIMETER OPERATIONAL THEORY

The radar velocimeter operates on the doppler effect which causes an apparent shift in frequency when the source of oscillation moves with respect to a reflecting surface.

The doppler frequency shift can be calculated from

\[ F_D = \frac{2 V_V}{\lambda} \]  \hspace{1cm} (15)

where

- \( F_D \) = frequency shift, Hz
- \( V_V \) = vertical velocity, fps
- \( \lambda \) = wavelength, ft

Wavelength can be calculated from

\[ \lambda = \frac{C}{F_0} \]  \hspace{1cm} (16)

where

- \( C \) = velocity of light
- \( F_0 \) = transmitter frequency

The frequency shift per fps of velocity can be calculated from

\[ \frac{F_D}{V_V} = \frac{2}{\lambda} \]  \hspace{1cm} (17)

The nominal transmitter frequency is 4,382 mHz. Substituting this in equation (17) yields 8.9 Hz/fps.

The radar velocimeter has a frequency to voltage converter that converts the doppler shift frequency to a voltage that is displayed in the cockpit meter as velocity in feet per second. The doppler shift frequency is recorded on the oscillograph recorder as a series of pulses. The frequency of these pulses can be determined by counting the number that occur per unit of time. The velocity can then be calculated by dividing this frequency by the factor obtained from equation (17). For example, if the doppler shift frequency is 89 Hz, the vertical velocity is 89/8.9 or 10 ft/sec.

When the velocimeter is moving toward a perfectly flat surface, the pulses recorded should be evenly spaced if the velocity is constant.
However, if the terrain has any roughness, the bumps will be sensed as a change in velocity and the pulses recorded will be unevenly spaced. If the general terrain is level but with some vertical waves, the average descent velocity can be obtained by choosing a long enough interval of time on the oscillograph record to compute the doppler shift frequency.

The accuracy of the velocity determined by data reduction of the oscillograph records is determined by the accuracy of the transmitted frequency and the type of terrain beneath the radar. For a perfectly flat terrain, the accuracy is ±0.25 percent or better. The accuracy over an uneven terrain is degraded somewhat. The amount of degradation is dependent upon the time interval selected to determine the doppler shift frequency and the characteristics of the terrain.

The cockpit meter displays vertical velocity on a 0-500 microampere meter which has a 0-30 fps scale with 0.05 fps increments. The reading accuracy of this meter is 1.5 percent of full scale, or about ±0.5 fps. The electronic accuracy of this reading is determined by the transmitting frequency and the transfer characteristic of the frequency to voltage converter. For a perfectly flat terrain, the accuracy is probably ±5 percent of full scale or better. Over uneven terrain, the accuracy would be degraded by an indeterminate amount, probably less than ±3 percent.
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