CONCLUSIONS

A computer program has been developed that can analytically determine whether the dynamic response of an aircraft to a given runway profile exceeds the established roughness criteria of $0.4 \, g$ and locate these rough areas on the runway.

1. Use: The program is general and will simulate most current commercial and military aircraft. The necessary data have already been assembled for many of these aircraft.

2. Efficiency: A C-9A takeoff simulation requires 70 s of central processing unit time on a CDC 6600 digital computer. This is just 30 s over real time and a number that is typical for all simulations.

3. Loads incurred on pavement: It would be easy to plot time histories of pavement loading rather than of aircraft vertical accelerations.

4. Aircraft parametric studies: The program can be used to perform parametric studies on aircraft to determine methods of reducing ground loads by modification of the aircraft.

A good example of a parametric study is the soft nose strut study, which found that by increasing the strut preload pressure of the nose landing gear, the vertical acceleration levels at the pilot's station were reduced significantly. This idea was tested with a Boeing 727-100 at Oklahoma City. The peak acceleration at the pilot's station was cut from $2 \, g$ peak to peak to $1 \, g$.

Figure 7 shows a histogram of the data from the taxi runs made at Oklahoma City; the overall aircraft response was significantly reduced throughout the entire test.

5. Accuracy: The comparison of the computed to the measured peak-vertical-acceleration levels was very good for all aircraft.

6. In addition to the identification of rough areas on runways, the program has other potential uses: i.e., runway repair evaluation—the program can be used to determine the minimum amount of repair required to bring the runway to acceptable standards from an aircraft-response standpoint—and prediction of response of other aircraft—the program can be used to predict the dynamic response of aircraft that will operate from a given runway in the future (e.g., a runway that is marginal for a Boeing 727 or a DC-8 may be unacceptable for the Concorde or a supersonic transport).

APPROACHES

The first indications of runway surface roughness are often verbal complaints by pilots. For this reason, the first roughness criterion investigated was human vibration. Human-response curves indicate that a peak vibration-acceleration level of about $0.4 \, g$ from about 2.0 to 20.0 Hz can be tolerated for at least 5 min, with a broad band of statistical scatter about this level. There are some theoretical and experimental data that show a few isolated peaks that reach or exceed $0.4 \, g$ on runways claimed to be rough by pilots. However, the existence of peaks only implies intermittent, rather than continuous, exposure, and it was therefore concluded that other sources of human-response data would be needed to establish a criterion.

In a second effort, an absorbed-power approach was investigated. A human can absorb 6 W of vibrational power for extended periods of time (1 or more min). However, for taxiing aircraft, the absorbed power exceeds 6 W for one or two approximately 5-s intervals during an entire run and, again, this occurs occasionally rather than continuously. Furthermore, the peak power is a function of the time interval over which the power is averaged. For example, if a 20-W peak for 1 s is averaged over 1 min, the resulting power level is negligible so that a rationale for establishing a power-averaging approach does not exist. The absorbed-power approach is more useful in locating rough regions than is the $0.4 \, g$ approach, but it still cannot be used to locate rough points precisely.

The third approach, using human criteria, was suggested by data from the Aerospace Medical Research Laboratory (AMRL) at Wright-Patterson Air Force Base, Ohio. These data were in disagreement with the absorbed-power results, and the $0.4 \, g$ criterion was con-
sidered obsolete. The vibrational levels observed in
taxiing aircraft are well below the comfort levels shown
in the AMRL criteria, and conservative results are in-
dicated. However, there is no other information avail-
able about human response to shock or psychologically
alarming effects at such low levels of vibration.

The effects of runway roughness on aircraft struc-
tural fatigue and avionics failure were investigated
briefly. However, criteria based on these subjects, in
addition to human response, rely on aircraft vibration
response. The use of aircraft response as a primary
tool for establishing roughness criteria is subject to
question, since it is an indirect approach to the problem.
Thus, the more direct approach of analyzing the profiles
rather than the responses was pursued.

RESULTS

The overall displacement roughnesses of 21 available
profiles are given below (1 mm = 0.039 in).

<table>
<thead>
<tr>
<th>Airport</th>
<th>Runway</th>
<th>o(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clovis, New Mexico</td>
<td>03</td>
<td>2.899</td>
</tr>
<tr>
<td>Palmdale, California</td>
<td>07</td>
<td>3.131</td>
</tr>
<tr>
<td>Dallas-Ft. Worth</td>
<td>17R</td>
<td>3.694</td>
</tr>
<tr>
<td>Dulles International, Virginia</td>
<td>01</td>
<td>3.821</td>
</tr>
<tr>
<td>Edwards Air Force Base, California</td>
<td>04</td>
<td>4.050</td>
</tr>
<tr>
<td>Grand Forks, North Dakota</td>
<td>35</td>
<td>4.277</td>
</tr>
<tr>
<td>Chicago-O’Hare</td>
<td>32L</td>
<td>4.429</td>
</tr>
<tr>
<td>Chicago-O’Hare</td>
<td>27L</td>
<td>5.430</td>
</tr>
<tr>
<td>Oklahoma City</td>
<td>TE</td>
<td>5.645</td>
</tr>
<tr>
<td>Charleston, South Carolina</td>
<td>15</td>
<td>6.630</td>
</tr>
<tr>
<td>Oklahoma City</td>
<td>12</td>
<td>6.753</td>
</tr>
<tr>
<td>Albuquerque</td>
<td>17</td>
<td>6.951</td>
</tr>
<tr>
<td>Baltimore-Washington International</td>
<td>28</td>
<td>7.067</td>
</tr>
<tr>
<td>Newark, New Jersey</td>
<td>22L</td>
<td>7.232</td>
</tr>
<tr>
<td>Offutt Air Force Base, Omaha, Nebraska</td>
<td>12</td>
<td>7.410</td>
</tr>
<tr>
<td>Chicago-O’Hare</td>
<td>22L</td>
<td>7.414</td>
</tr>
<tr>
<td>John F. Kennedy, New York</td>
<td>13R</td>
<td>7.674</td>
</tr>
<tr>
<td>Buffalo</td>
<td>05</td>
<td>9.219</td>
</tr>
<tr>
<td>Washington National</td>
<td>18</td>
<td>9.460</td>
</tr>
<tr>
<td>Albany</td>
<td>19</td>
<td>11.272</td>
</tr>
<tr>
<td>Thule</td>
<td>16</td>
<td>13.400</td>
</tr>
<tr>
<td>Avg</td>
<td></td>
<td>7.082</td>
</tr>
</tbody>
</table>

The following general conclusions and observations have
been made.

1. Runway 03 at Clovis is the smoothest runway.
2. Runway 16 at Thule is the roughest runway.
3. Runway 28 at Baltimore-Washington represents
   the average runway.
4. Although runway TE at Oklahoma City has an
   above average overall index, there is one severe bump
   that is probably in need of local repair, but only a sta-
   tistical analysis can determine this quantitatively.

SUMMARY OF CONCLUSIONS
AND RECOMMENDATIONS

Runway-roughness-rating methods based on aircraft-
response properties are not recommended. These
methods consider structural, component, or human-
failure mechanisms and cannot be correlated precisely
with local bumps that need repair. Knowledge of aircraft
responses can be useful for evaluating the effectiveness
of a repair plan, but cannot be used in constructing the
repair plan. The response data can also be analyzed
statistically to obtain information about amplitude and
frequency content for studying aircraft vibration. The
collection of such data is recommended, but not as the
primary information on which to base a repair plan.

The statistical analysis of filtered profile data is
recommended as a direct method of assessing runway
profile roughness. The approach described here is only
a beginning, as only the displacement standard deviation
has been extracted as a primary index of roughness. The
overall properties should be expanded to consider slope
and slope-change information, and these properties are
only half of the necessary criteria; the statistical analy-
sis of the peaks will be necessary before the information
is complete. Finally, the statistical information must
be correlated with subjective pilot ratings.

Nondestructive Testing of Airport Pavements

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A study of nondestructive testing techniques for the evaluation of airport
pavements is summarized. The report includes (a) the selection and prep-
paration of specifications for nondestructive testing of airport pavement
systems, (b) the development of a methodology for evaluating the load-
carrying capacity of airport pavement systems by using the equipment
selected, (c) the development of an evaluation procedure based on this
methodology, and (d) the development of a mathematical model that
describes pavement response to dynamic loading.

The current methods for evaluating the load-carrying
capacity of airport pavements require direct sampling
techniques that are both costly and time-consuming.
Often, these methods require the closing of the pavement
facility to traffic operations, which necessitates the re-
routing or rescheduling of both of aircraft. With the
number of traffic operations increasing rapidly, even
the brief closing of a pavement facility can result in in-
convenience to the traveler and higher costs to the air
carrier. Also, the increasing gross masses and in-
creasing numbers of operations of aircraft make the
need for accurate and frequent evaluations of pavement
systems extremely important to the airport owner be-
cause many facilities will need strengthening or rehabil-
itation to meet these increased demands. Given these
considerations, the need for a procedure that permits
rapid evaluation with a minimum of disturbance to nor-
mal traffic operations is evident. The use of nonde-
structive testing techniques to determine the pertinent
characteristics of pavement systems offers the best
promise of serving this need.

PURPOSES

The purposes of this study were to

1. Select and prepare specifications for equipment
to be used for nondestructive testing of airport pavement

systems,