Type of Pavement	Width of Pavement (m)	Average Offset (m)	
		Value and Direction	Standard Deviation
Runway			
Landings	45.7	0.27 to 0.48 left	2.1 to 3.1
	61.0	0.24 right to 0.70 left	2.7 to 3.4
Takeoffs	45.7	0.15 to 0.37 left	1.8 to 2.5
	61	0.70 to 0.76 left	2.3 to 2.5
Straight taxiway	22.8	0.64 right	0.76 to 1.2
	30.5	0.97 right	1.8
High-speed runway exit	Variable	–	2.4 to 3.2

3. The overall impact of such factors as night operations, crosswinds, and wet pavements is not a significant influence on the distribution of aircraft traffic.

ACKNOWLEDGMENT

This paper is a summary of a report to FAA (2).

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Effects of Dynamic Loads on Airport Pavements

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A study of the responses of typical flexible and rigid airport pavements to static and dynamic loading is summarized. Two series of full-scale tests using instrumented aircraft and runways were made. Among the results were that (a) both types of pavements exhibited both elastic and inelastic responses; (b) these types of responses must be separated to interpret the data; (c) two different types of displacement responses (inertial and noninertial) are present; (d) bow waves and elastic vertical expansions about the wheels occur in both types of pavements; (e) the vertical pressures in both types of pavements are totally recoverable and elastic; (f) no basic aircraft ground operating mode induces pavement responses greater than those occurring for static load conditions, although under unusual conditions, such responses might occur; (g) pavement thicknesses can be reduced in the interiors of runways, but the pavement in exit areas of flexible runways should be stronger than that of main runways; (h) inelastic behavior is highly dependent on temperature, rate of load application, and load history; (i) in the velocity range of static load to low-speed taxi, inelastic displacements can be larger than elastic ones; and (j) the elastic behavior of stiff pavements is almost constant. Because the elastic and inelastic displacement behavior of pavements correlates to the behavior of the Waterways Experiment Station pavements test sections under simulated aircraft loads and wheel configurations and distributed traffic to the behavior of actual pavements under actual aircraft operations, further investigations of dynamic load effects can probably be conducted on pavement test sections of limited size.

Because of reports of pavement distress resulting from current commercial aircraft loads and growing concern over the possibility of further detrimental aircraft dynamic-load effects on airport pavements, the Federal Aviation Administration has sponsored a study of this problem. The study consisted of a literature survey, computer analyses to determine aircraft loads and pavement responses, scaled pavement tests, and correlations between experimental and analytical data. In general, it was concluded that aircraft dynamic wheel loads have had a significant effect on portions of airport pavements. Specifically, the study showed that the primary effects that influence pavement response to dynamic loads are

1. The increased magnitudes of aircraft wheel loads that result from aircraft modes of operation, pavement unevenness, and aircraft structural characteristics during moving ground operations and
2. The dynamic load phenomena associated with the materials used in the construction of both rigid and flexible pavements.

For a given aircraft and level of pavement unevenness, the loads imposed on a runway can be accurately defined for various ground operations. On the other hand, there has been a serious lack of the information necessary to obtain an accurate description of pavement response to dynamic loads.

PURPOSE

The study was undertaken to provide experimental pavement-response data so that the significance of dynamic loads on airport pavements could be evaluated. Specifically, the basic purpose of the study was to determine the relations between the responses of typical flexible and rigid runway pavements and static and dynamic loads. The magnitudes of the dynamic loads and the depths to which pavement structures are affected by both static and dynamic loads were determined, and the relation between aircraft ground speeds and dynamic loads were investigated.

SCOPE

Two series of full-scale tests using instrumented aircraft and both flexible and rigid instrumented runways were conducted to provide the data needed. One series of tests was conducted during the winter of 1972 when the average temperature of the top pavement layer was between 1.7 and 12.8°C (35 to 55°F), while the second series was conducted (on the flexible pavement only) during the summer of 1974 when the average temperature of the top pavement layer was between 28.9 and 46.3°C (84 to 116°F). Instrumentation systems were installed aboard aircraft to measure and record the three components of force of each of the main-gear assemblies. Instrumentation systems were also installed at various elevations in the pavements to measure the pavement responses to aircraft loads as relative displacements and pressures. The key element in this experimental approach was the recording of a common time base for the aircraft-load and the pavement-response measurements. This control provided a means of correlating the responses of the aircraft and pavement structures to within 1 ms. The locations of the instrumented pavement test sites were

Figure 1. Test sites at NAFEC Airport.

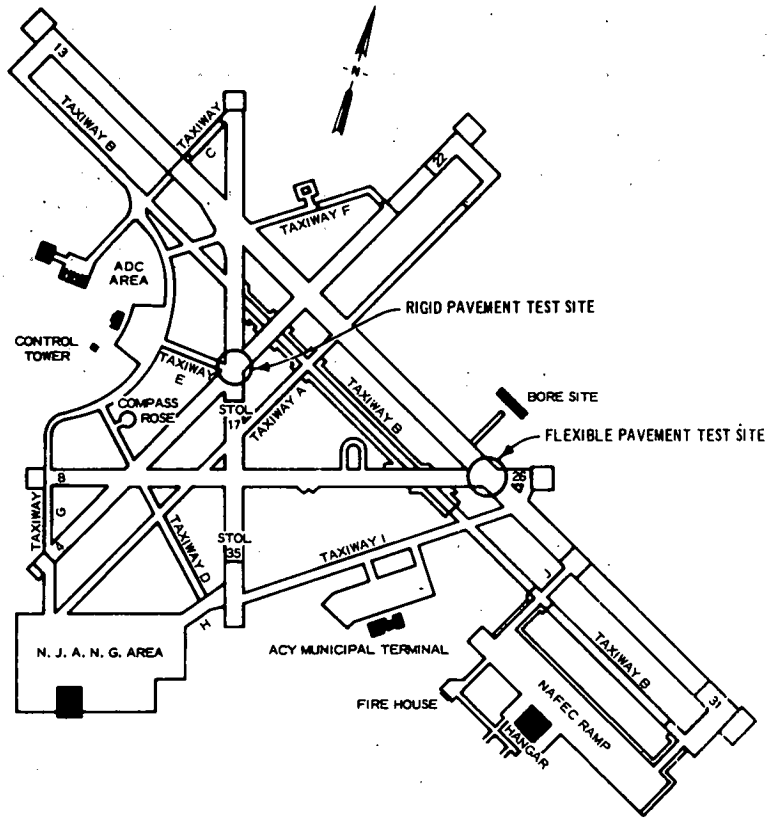


Figure 2. Arrangement of flexible pavement instrumentation.

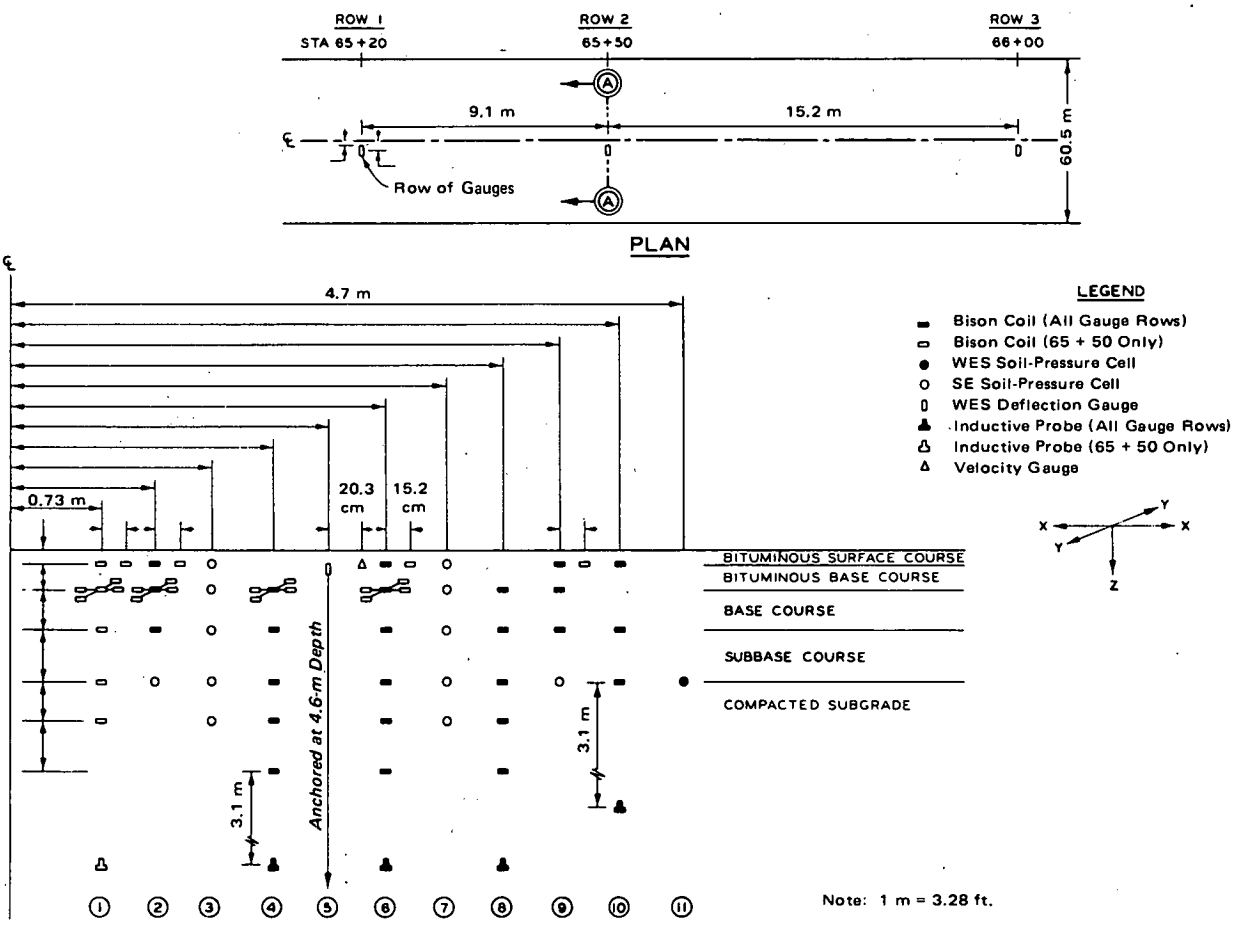
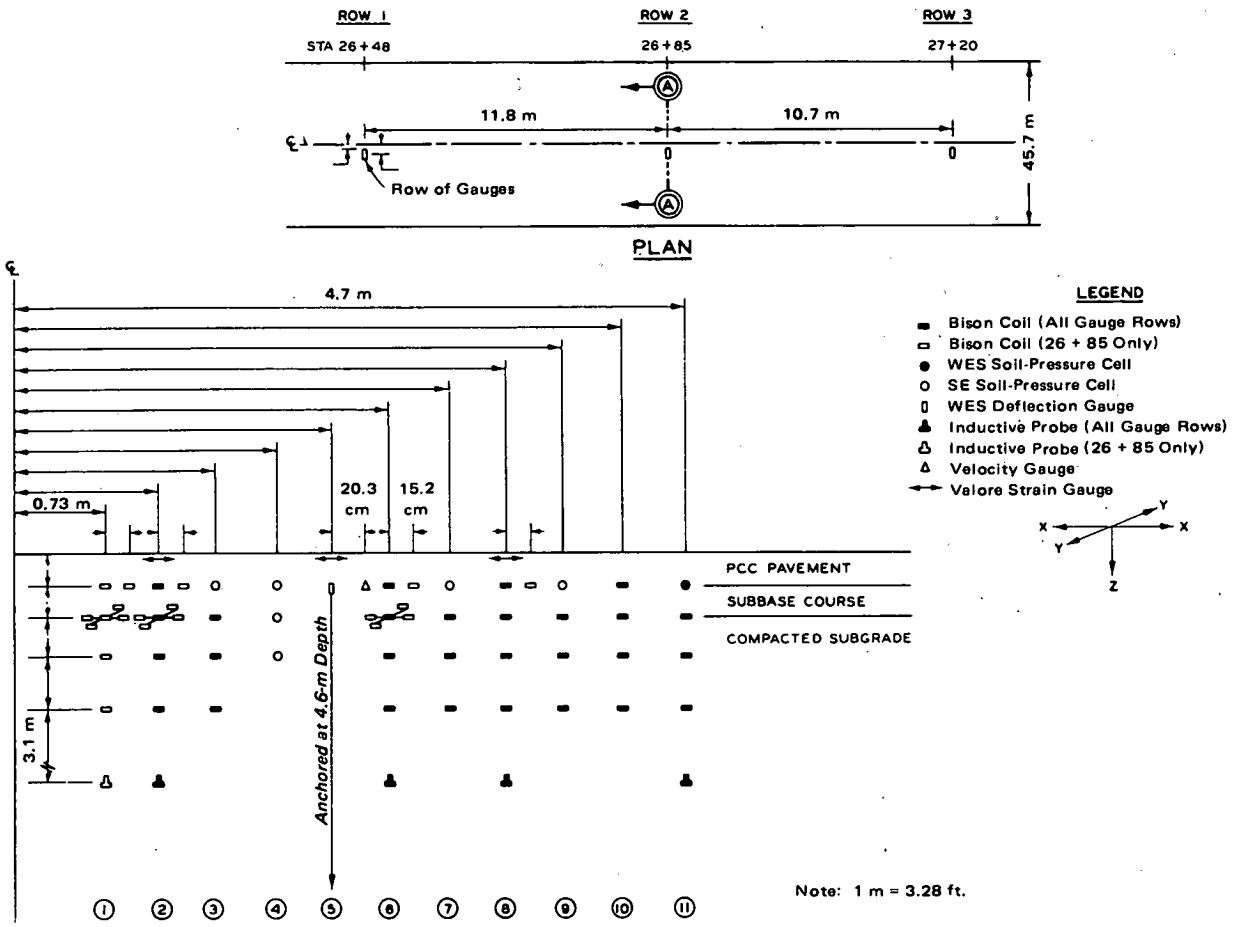


Figure 3. Arrangement of rigid pavement instrumentation.



selected so that all possible modes of aircraft ground operation could be investigated.

TEST PROGRAM

The instrumentation packages were installed in the pavement structures of runways 04-22 and 13-31 at the National Aviation Facilities Experimental Center (NAFEC) Airport, Atlantic City, New Jersey, at the sites indicated in Figure 1.

A 24.4-m (80-ft) long segment of runway 13-31 located at its intersection with runway 8-26 was selected as the flexible pavement test site. This test site allowed the collection of typical response measurements during landing and at the point of rotation for takeoff as well as during low- and high-speed taxiing, braking, and turning operations. This particular site was in a portion of the runway that was being reconstructed, which was of great advantage for the installation of the instrumentation. After the reconstruction, the flexible pavement in this area consisted of 7.6 cm (3 in) of bituminous surface course, 15.2 cm (6 in) of bituminous base course, 22.9 cm (9 in) of base course consisting of the crushed and mixed original pavement surface and base courses, and 30.5 cm (12 in) of subbase course constructed from the original subbase course over a compacted subgrade.

A typical experimental arrangement of the flexible-pavement instrumentation system is shown in Figure 2. The arrangement included Bison coils, SE soil-pressure cells, waterways experiment station (WES) deflection gauges and soil-pressure cells, inductive probes, and velocity gauges. In addition, thermistors were installed on the pavement surface and at depths of 7.6, 15.2, and 22.9 cm (3, 6, and 9 in) within the pavement structure.

A 22-m (72-ft) long segment of runway 04-22 was instrumented at its intersection with runway 17-35 to form the rigid pavement test site. The pavement structure in this area consisted of 17.8 cm (7 in) of portland cement concrete pavement and 20.3 cm (8 in) of subbase course over the compacted subgrade. The concrete was removed, and the gauges were installed in holes cored through the underlying material.

The instrumentation system installed in the rigid pavement test site was similar to that in the flexible pavement test site. Figure 3 shows a typical arrangement, which included Bison coils, inductive probes, deflection gauges, Valore strain gauges, SE and WES soil-pressure cells, and velocity gauges. Thermistors were installed on the surface of, at the bottom of, and at a depth of 8.9 cm (3.5 in) in two slabs of the pavement.

A system of laser sources and detectors was installed along the edges of the runways such that a beam was projected directly above and parallel to each instrumentation gauge row. An electrical impulse was generated when the wheels of the instrumented aircraft passed between the source and the detector, thereby signaling the instant at which the wheels were directly over the gauge row. The lateral position of the aircraft was determined by visual inspection of a stripe of flour and water solution painted on the surface of the runways adjacent and parallel to each gauge row.

A synchronized common time signal was recorded on both aircraft and ground-data tapes. This provided the

means by which the pavement response could be correlated with the corresponding aircraft load. With the exception of the thermistors, all the instruments were recorded simultaneously on magnetic tapes, and all ground-data tapes contained the time code and laser signals. Temperatures were recorded on paper tape.

An instrumented B-727 was used for the cold weather testing in 1972, and a similar B-727 and a C-880 were used for the warm weather testing in 1974. The aircraft were instrumented to measure the force transmitted to the pavement structure. On-board instrumentation for all three aircraft included signal conditioning equipment, a time-code generator (synchronized with the ground time-code generator for correlation of the test results), and a 14-track analog magnetic tape recorder.

Data were collected for 408 aircraft operations during the cold weather tests. Of this total, 203 operations were on the flexible pavement test site, and the remaining 205 were on the rigid pavement test site. During the warm weather tests, data were collected for 281 aircraft operations on the flexible pavement test site.

The following types of tests were performed during both cold and warm weather tests:

1. Static load tests—The aircraft was positioned over each gauge row and data collected to provide a base for comparison with the data from the dynamic load tests and a verification of the capability of the instrumentation system.
2. Dynamic load tests—Various aircraft ground operations were conducted on the test sites, and the pavement responses and aircraft dynamic loads were determined for the following aircraft operating modes: (a) creep-speed taxi at 5.6 to 14.8 km/h (3 to 8 knots), (b) low-speed taxi at 27.8 to 55.6 km/h (15 to 30 knots), (c) medium-speed taxi at 83.4 to 148.2 km/h (45 to 80 knots), (d) high-speed taxi at 157.5 to 240.9 km/h (85 to 130 knots), (e) high-speed braking at 240.9 to 83.4 km/h (130 to 45 knots), (f) takeoff rotation at 157.5 to 240.9 km/h (85 to 130 knots), (g) touchdown, (h) high-speed braking with reverse thrust, and (i) turning at 7.4 to 55.6 km/h (4 to 30 knots).

ANALYSIS OF DATA AND RESULTS

In general, all instrumentation performed satisfactorily. The instrumentation responses were reduced by automatic data processing (digital) techniques and showed the following results:

1. Both flexible and rigid nonconditioned pavements exhibit both elastic (including viscoelastic) and inelastic behavior. (Conditioning is a test procedure in which a pavement point is loaded repeatedly before recording its responses. By this procedure, inelastic response, which can be erratic, is made to approach zero; therefore, measured response then appears to be stable. However, while this type of conditioning temporarily eliminates the inelastic movements, it is not really representative of behavior under actual traffic loading because traffic is randomly distributed and approaches a normal distribution with time.) The magnitudes and directions of movement of the inelastic responses were controlled by the gear-to-gauge offset distance. There were changes in direction of the inelastic response and upward movement at the various offsets and in the immediate gauge vicinity, but generally the elastic and inelastic responses exhibit symmetry and repetition.
2. To be able to fully interpret and analyze the response data of the nonconditioned pavement, the elastic and inelastic responses have to be separated (they occur simultaneously) and treated independently. The measured responses could not be completely analyzed unless the inelastic behavior was fully accounted for.
3. Two different types of displacement responses—that of the total pavement structure as assumed to be referenced to infinity (inertial reference) and that of the individual pavement-structure element referenced internally to each element (noninertial reference)—act in both flexible and rigid pavements. Each type of response exhibits both elastic and inelastic behavior.
4. Bow waves in front of and elastic vertical expansions behind and adjacent to the wheels occur within the structural elements (noninertial reference) of both types of pavement structures under moving aircraft operations.
5. The vertical pressures of both flexible and rigid pavements are totally recoverable and elastic. On removal or passage of a load, no residual pressures appeared to be acting; therefore, the inelastic behavior did not seem to induce residual vertical pressures. The pressure cells appeared to be carried with or ride within the pulsating structures.

The investigation of the relations between the pavement response and the aircraft dynamic loads found the following results:

1. The B-727 aircraft dynamic load tests in 1972 (cold weather) and 1974 (warm weather) on the nonconditioned flexible pavement structure and in 1972 on the nonconditioned rigid pavement structure showed that none of the basic aircraft ground operating modes induced pavement responses (elastic plus inelastic) greater than those occurring for static load conditions, even though the aircraft dynamic loads were as much as 1.2 times the static load. The elastic response alone also generally indicates this to be true. The pavement surfaces were relatively smooth in the test site areas.
2. However, extrapolation of the test results indicated that for stiff pavement structures, such as the rigid pavement at all times and the flexible pavement in cold weather, unusual conditions of large dynamic loading that could result from such conditions as rougher surfaces than that at NAFEC or holes or bumps could possibly cause responses larger than those that occur under static loading. This is possible because the inelastic response of the stiff pavements is low, but their elastic response is essentially of a constant magnitude with rate of load applications. The larger-than-static-load response that could occur should be entirely elastic and not detrimental to the pavement structure except by contributing to an increase in elastic fatigue damage.
3. The gradually reduced elastic response and the reduced inelastic response at high speeds indicated that pavement thickness can be reduced in the interiors of runways.
4. The measured aircraft loads showed that high horizontal loads were applied to the pavement surfaces during turns. Because of these high loads and to prevent excessive deterioration in turn areas, the pavement in exit areas of flexible pavement runways should be strengthened or be stronger than the main runway.
5. The tests showed that inelastic behavior is highly dependent on temperature, rate of load application, and load history (magnitude of load and lateral position of aircraft).
6. Inelastic displacements measured within the velocity range of static load to low-speed taxi were larger than the elastic displacements.
7. The tests showed elastic behavior to be almost constant for stiff pavement structures (rigid and low-temperature bituminous pavements) and the probable viscoelastic effects to be more pronounced at high temperatures in bituminous materials.

8. At the deepest layers monitored—i.e., 99 to 130 cm (39 to 51 in) for the flexible pavement and 38 to 61 cm (15 to 24 in) for the rigid pavement—the responses to various modes of aircraft operation of the flexible and rigid pavements were 10 and 30 percent respectively of their surface responses.

9. Elastic and inelastic displacement behavior and response can be accurately modeled mathematically.

10. The elastic and inelastic displacement behavior directly correlates the behavior of the WES pavement test sections under simulated aircraft loads and wheel configurations and distributed (not conditioning) traffic to the behavior of an actual pavement under actual aircraft operations (NAFEC tests). This correlation means that any further investigation of dynamic load effects can probably be conducted on pavement test sections of limited size.

11. Inelastic behavior occurred in both the nonconditioned flexible and the rigid pavement structures and may possibly be a common characteristic that links the performance of all types of pavement. In fact, it may be the major controlling factor or mechanism for pavement performance and life because it can be the primary movement for static and low-speed operations.

RECOMMENDATIONS

The thickness required of pavements subjected to parked or slow-moving aircraft should be based on the static mass of the aircraft, as is the current practice. This applies to the parking aprons, taxiways other than high-speed exit areas, and runway ends. In high-speed exit areas, runway interiors, and other areas that are subjected to high-speed aircraft operations only, the design should be based on an analysis of the design loading to the pavement and the pavement response to dynamic loading. In high-speed exit areas, high horizontal loads are applied to the pavement surface and should be considered in the design. Because of the large loads and thus the likelihood of excessive deterioration in turn areas, the pavement surface in exit areas of flexible pavement runways should be strengthened or be stronger than the main runway. In runway interiors, the NAFEC test data indicate that thickness reductions could be considered. However, to take full advantage of the NAFEC test data in pavement design, more knowledge is needed concerning pavement failure mechanisms and deterioration growth functions and causes.

ACKNOWLEDGMENT

This paper is a summary of a series of reports to FAA (1, 2, 3).

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Dynamic Response of Aircraft to Pavement Unevenness

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A computer program was developed to simulate aircraft dynamic response to runway roughness during taxiing and takeoff. The mathematical model has rigid-body degrees of freedom of pitch, roll, and vertical and horizontal translation and up to 30 flexible modes of vibration. Runway profile data measured at approximately 0.61-m (2-ft) intervals is input into the program and used as the model forcing function. A different profile is encountered by each landing gear. All the necessary landing-gear and airplane data were collected for the following aircraft: Boeing—KC-135; B-52C,G,H; T-43 (737); AMST Comp (YC-14); 727-100; 727-200; 707-320; and 747; McDonnell Douglas—AMST Comp (YC-15); C-9A,B; DC-8-63; DC-9-40; DC-10-10; and RF-4C; Lockheed—C-130E; C-5A; C-141; and L-1011; and other—F-111A; A-37; and CT-39. Each of these aircraft was simulated; a comparison of the responses of several different military aircraft showed that the simulated accelerations at the pilot stations were within 5 to 10 percent of the measured values. Typical computer run times were less than 60 s on a CDC 6600. The intended purpose of the program was to locate the rough areas of a runway by using the ±0.4*g* criterion as a limiting vertical acceleration. Additional useful applications of the program are (a) analysis of pavement dynamic loading; (b) runway repair evaluation; (c) evaluation of the dynamic response of new aircraft, such as the Concorde and supersonic transport, on a given runway profile; and (d) the performance of aircraft parametric studies, such as that of the high preload-pressure, nose landing-gear strut, to determine methods for reducing aircraft ground loads.

The problem of pavement unevenness is of concern to many persons in the airport and aircraft industries: Runway contractors are required to build smoothness into new and overlaid runways. Airport owners and operators are required to ensure that smoothness is maintained. Aircraft manufacturers are required to design their aircraft with good ride quality and structural integrity for both air and ground operations. One of the objects of each is to minimize aircraft structural damage and passenger and crew discomfort during ground operations.

Figure 1 (1) shows the derivation of the current roughness criterion used to set maximum allowable levels of vertical acceleration. This is a human-comfort, rather than an aircraft structural, criterion. Most current passenger aircraft have rigid-body natural frequencies of less than 10 cycles/s. At these frequencies, the acceleration-versus-frequency curve is relatively flat and corresponds to a value of approximately ±0.4 *g*. Essentially then, if the vertical acceleration level at any point along the fuselage exceeds ±0.4 *g*, measured from zero to peak, that particular section of that runway is too rough for that particular aircraft. Next, a technique for determining when the acceleration-criterion level has been exceeded must be established. There are two basic methods for this: aircraft instrumentation and testing or aircraft simulation.

Aircraft testing requires the instrumentation of an aircraft, the calibration of the instrumentation, and data reduction and interpretation. It involves expensive