NASA
Technical
Paper
2353

September 1984

Validation of an Active Gear, Flexible Aircraft Take-Off and Landing Analysis (AGFATL)

John R. McGehee

NASA

NASA
Technical
Paper
2353

1984

Validation of an Active Gear, Flexible Aircraft Take-Off and Landing Analysis (AGFATL)

John R. McGehee

Langley Research Center
Hampton, Virginia

Summary

The logic and equations of a series-hydraulic active control gear were incorporated into a multi-degree-of-freedom flexible aircraft take-off and landing analysis (FATOLA) to generate a computer program for active gear, flexible aircraft take-off and landing analysis (AGFATL). The results of previously conducted experimental investigations consisting of shaker tests, drop tests, and simulated-landing tests of passive and active versions of a general aviation airplane main gear are compared with computed data to validate the AGFATL computer program.

Comparisons of experimental and analytical data for shaker tests (forced vibrations) and drop tests show good agreement for both the passive and active gears. Experimental data for the landing tests were influenced by large unmeasured strut-binding friction forces. The inclusion of these friction forces in the analytical simulations was difficult, and consequently only fair to good agreement between experimental and analytical data was obtained. An overall assessment of the results from the investigation indicates that (despite the susceptibility to frictional forces of the gear employed in this investigation) the AGFATL computer program is a valid tool for the study and initial design of series-hydraulic active control landing-gear systems.

Introduction

In large airplanes, dynamic loads and vibrations resulting from landing impact and traverse of uneven runways and taxiways are recognized as significant factors in causing fatigue damage and dynamic stressing of the airframe structure. The ground-induced structural vibrations also result in crew and passenger discomfort and, on large flexible airplanes, can reduce the pilot's capability to control the airplane during high-speed ground operations. These problems have been encountered with some currently operational transport aircraft, as discussed in references 1 and 2. Such problems will be magnified for supersonic-cruise airplanes because of the increased structural flexibility inherent in their slender-body design, their thin-wing construction, and their high take-off and landing speeds. For example, investigations of the ground-handling qualities of one particular design of a supersonic transport conducted in the United States in the 1960's revealed extremely high vibration levels in the crew compartment during the take-off roll (ref. 3). One potential method for improving ground operations of supersonic-cruise airplanes is the application of active control technology to the landing gears to limit the ground loads applied to the airframe.

Analytical studies (refs. 3 to 5) have been conducted to determine the feasibility and potential benefits of applying active load control to the airplane main landing gear to limit the ground loads applied to the airframe. A limited-degree-of-freedom, nonlinear active control landing-gear analysis and computer program (ACOLAG) was developed for studying active control landing-gear concepts (ref. 5). In the same time frame, a multi-degree-of-freedom, stiff airframe take-off and landing analysis computer program (TOLA) was obtained from the Air Force Flight Dynamics Laboratory and modified to include flexible airframe characteristics (FATOLA). (See refs. 6 to 12.)

Computer program ACOLAG was employed to study the potential of a series-hydraulic active control landing-gear concept. Based on the favorable results of this study, an electronic control and a hydraulic power unit were designed, fabricated, and tested with a modified main gear from a general aviation airplane to validate hardware performance. The results of the limited tests are reported in reference 13. To further demonstrate the feasibility and the potential of the series-hydraulic active control landing gear, shaker tests, drop tests, and simulated-landing tests of passive and active versions of the general aviation airplane main gear were conducted (refs. 14 and 15).

The logic and equations for the series-hydraulic active control gear developed in ACOLAG have been incorporated in FATOLA to generate a computer program for multi-degree-of-freedom active gear, flexible aircraft take-off and landing analysis (AGFATL). (See ref. 16.) The purpose of this paper is to validate the AGFATL computer program with data from shaker tests, drop tests, and landing-simulation tests of passive and active versions of the main landing gear from the general aviation airplane.

Experimental Data

The experimental data for validating the AGFATL computer program were obtained with passive and active versions of a modified main landing gear from a general aviation airplane. The modified main landing gear, feedback instrumentation, and control hardware for the active control landing gear are shown schematically in figure 1. Closure of the hand valve permitted passive operation of the gear by isolating the servovalve from the modified gear. Shaker tests conducted by the Air Force Wright Aeronautical Laboratories (ref. 14) compare the responses of the passive and active gears to various sinusoidal and step bump profiles that might be encountered during the taxi/rollout mode. Drop tests and landing tests conducted at the Langley Aircraft Landing Dynamics Facility to demonstrate the feasibility and the potential of the active gear during touchdown impact and landing rollout are reported in reference 15.

Shaker Tests

The experimental setup for the shaker tests is shown in figure 2. The shaker tests were conducted for the taxi/rollout mode with the landing gear rigidly attached to the 93-slug (3000-lbm) drop-tower bucket. The landing-gear strut axis was oriented vertically, and the drop-tower bucket was restrained to vertical motion. This restraint minimized the binding friction in the gear. The shaker was programmed to provide various haversine and step inputs to the gear through the tire. The haversine inputs consisted of five forcing cycles at frequencies varying from 1 to 20 Hz with double amplitudes varying from 2.0 in. at the lower frequencies to 0.5 in. at the higher frequencies. The step input consisted of one forcing cycle, a compressive step input, and (when strut motion subsided) a step return to the initial table position. The step initial input had a 0.5-in. amplitude, and the amplitude was increased by 0.5-in. increments to a maximum of 4.5 in. or until either the tire or the strut bottomed during the compressive input. The forcing function was applied vertically in all cases (no horizontal inputs).

Drop Tests

The experimental setup for the drop tests and landing tests is shown in figure 3. The drop tests of passive and active versions of the modified main gear were made with a pitch attitude of 0° (pitching beam locked in a horizontal position), zero ground speed, and touchdown sink rates from 3 to 5.5 fps. Since the gear longitudinal axis was aligned vertically and no horizontal forces were involved, these tests demonstrated the effectiveness of the active gear when strut-binding friction was minimal.

Landing Tests

The landing tests were conducted for touchdown pitch attitudes of the pitching beam from 2° to 13°, ground speeds from 8 to 80 knots, and sink rates from 3 to 5.5 fps. The landing tests provide a more realistic representation of the loads and motions imposed on an airplane than those obtained during vertical-drop tests. The principal difference between these types of tests is that moments resulting from vertical and horizontal forces developed at the axle because of aircraft pitch attitude and wheel spin-up at touchdown induce strut-binding friction forces in the landing tests.

AGFATL Capabilities

The capabilities of the active gear, flexible aircraft take-off and landing analysis (AGFATL) computer program, along with a schematic representation of the active shock strut, are shown in figure 4. The program provides a comprehensive simulation of aircraft take-off and landing phases of operation with conventional or series-hydraulic active gears. Effects simulated in the program include (1) aircraft aerodynamic control and performance during glide slope, flare, landing, and take-off when subjected to conditions such as varying wind speeds and directions, engine failures, brake failures, landing-gear strut failures, control variable limits, and control response times; (2) landing-gear loads and dynamics for aircraft having a minimum of three gears and a maximum of five gears; (3) aircraft with a maximum of four engines; (4) selective engine reversing; (5) ground effect aerodynamics; (6) drag chute, speed brakes, and spoiler aerodynamics; (7) constant or skid-controlled braking; (8) take-off from or landing on runways or aircraft carriers; (9) inclined runways and/or runway elevation perturbations; (10) rudder steering, nose-gear steering, or combined rudder and nose-gear steering; and (11) conventional oleo-pneumatic and/or series-hydraulic active control landing-gear shock struts. The construction of the program is modular so that glide slope, flare, landing, and take-off phases may be evaluated separately or in combination. The program also includes options for rigid or flexible airframe structural characteristics and passive or series-hydraulic active gear types.

Detailed analytical studies of aircraft ground operations generally require a large amount of computer operational time because of the large oscillatory variations in the loads and motions of the aircraft. To alleviate this problem, the AGFATL computer program also has staging and restart capabilities. The staging capability permits the user to change values of the input data to represent variations of the input variables which may occur during the landing or take-off simulations. The restart capability permits the user to restart the program from any point in the time history where data have been staged into the program. This technique is useful and efficient if the program fails to execute to a normal termination or for the analysis of landing rollout over various simulated runway roughness conditions. For example, to investigate runway roughness conditions, the program can be restarted at a time in the simulation just prior to airplane encounter with the desired runway roughness without rerunning the entire landing simulation.

Analytical Simulation Techniques

Since the AGFATL computer program is designed for analyzing during ground operations the loads and motions of an airplane with a minimum of three landing gears, the input data were modified to simulate the test data for the single gear. The following sections discuss the modifications for the shaker tests, drop tests, and landing tests.

Shaker Tests

Since no aerodynamic, control, or engine forces existed during the shaker tests, the aerodynamic, autopilot, thrust, and engine subroutines of AGFATL were not called. A minimum of three gears is required in the computer program; however, since only a single main gear was tested, the nose-gear attachment to the airframe was specified as a large negative value so the nose gear would not contact the surface. Furthermore, since the drop-tower-bucket center of gravity and the single-gear strut longitudinal axis were aligned, this condition was simulated by placing the two main gears in the transverse vertical plane containing the center of gravity of the airplane. Since it was necessary to use two main gears, the force applied to the airplane mass would be double the force of the single gear used in the shaker tests. Therefore, to obtain similar dynamic characteristics, the mass of the simulated airplane was input as twice the mass of the drop-tower bucket.

Angular degrees of freedom were not present during the shaker tests; therefore, the pitch, yaw, and roll attitudes of the simulated airplane were input with zero values, and significant changes in these attitudes were prevented by inputting very large moments of inertia about the pitch, yaw, and roll axes.

To simulate the sinusoidal and step inputs of the shaker, the runway elevation perturbation capability was used; however, the AGFATL computer program is not capable of simulating vertical-force inputs to the gear at zero ground speed. In the shaker tests, the gear rests on the shaker table and supports the mass of the drop-tower bucket; therefore, to use the runway elevation perturbation capability, the airplane must have a ground speed with the gears supporting the airplane mass at the designed static deflection of the shock strut and the tires. To reach this condition, the simulated airplane was placed on a glide slope with the main gear tires slightly above the runway with a ground speed of 71 knots and a sink rate of 3 fps. To expedite reaching the desired rollout condition, a large damping force was input to the gear struts to provide rapid damping of strut and airplane motions resulting from the impact phase. When the gear struts were supporting the airplane mass at the designed static strokes, the large damping force was removed from the struts (by use of the staging capability), and the sinusoidal runway elevation perturbations were introduced. To simulate the 1.3-Hz forcing function of the shaker, five cycles of elevation perturbations with double amplitudes of 2 in. and wavelengths compatible with the 71-knot ground speed were staged into the computer program.

The wheel had no rotational velocity during the shaker tests; therefore, the table containing ratios of ground friction to tire slip in the program had to be bypassed by introducing a nominal positive velocity value greater than the tire-ground-plane velocity. This procedure results in bypassing the table of friction-slip ratios and in setting the longitudinal and transverse ground reaction force components to zero.

The step bump tests were simulated by using the restart capability of the AGFATL computer program. The time history of the landing was restarted subsequent to the time at which the strut and airplane touchdown impact motions had subsided. The staging capability was used to remove the runway sinusoidal perturbations and to introduce step elevation perturbations to the runway surface.

Drop Tests

The drop tests were conducted with the gear attached normal to the pitching beam that was restrained at a pitch attitude of 0°. The lift force was simulated (by use of the staging capability) by introducing a generalized vertical-force vector equal to values of the lift recorded during the tests. Since no ground speed was involved in these tests, the following inputs were modified to simulate the drop test: the flight path angle was input as −90°, the drop velocity at touchdown was input as the airspeed, and the pitch angle was input as 0°.

Landing Tests

The landing tests were conducted with the single main gear attached to the pitching beam of the test fixture. The pitching beam had a mass of one-half the airplane mass (ref. 15). Aerodynamic lift and drag forces, aerodynamic elevator control force, and nose-gear force were simulated in the test program; however, aerodynamic lift and drag forces in the test program were not compatible with the aerodynamic coefficients required as input to the computer program. Therefore, these forces were represented in the computer program by generalized z-axis (lift) and x-axis (drag) body-oriented force vectors modified as a function of time by use of the staging capability of the program.

The aerodynamic elevator control force and the nose-gear force (which were internal forces relative to the test fixture) were represented in the program by a generalized moment vector about the pitch axis. This moment vector was modified during the time history to reflect changes in the simulated test values of the elevator and nose-gear forces.

The presence of large binding-friction forces in the main gear strut during the landing tests was discussed in reference 15. In addition, the test fixture was also subject to frictional forces which would not be present during an aircraft landing. The light aircraft main gear used in the test program reported in reference 15 was very susceptible to the generation of large binding-friction forces due to the large ratio of stroke to piston diameter. The gear was particularly susceptible to large binding-friction forces during the touchdown impact phase, since the spacing between the shock-strut bearing surfaces is a minimum when the strut is fully extended. Also, this gear had previously been subjected to severe test conditions (ref. 13) that resulted in large bending moments and elastic deformations of the gear, which may have caused bearing wear and aggravated the susceptibility to binding friction.

The computer program AGFATL simulates the strut-binding friction resulting from tire spin-up and encounters with changes in runway elevation but is not readily adaptable to binding friction resulting from deformations in the strut due to wear. The program also simulates the Coulomb type of friction resulting from the fit of the bearings relative to the cylinder and the piston. However, a smoothing technique (ref. 12) is included to prevent sudden changes in magnitude and direction of the friction force when the strut velocity passes through zero during changes in direction.

Analytical simulation of the strut and test fixture frictional forces was accomplished by staging changes to the strut Coulomb friction and the generalized vertical-force vector to represent strut-binding friction and test fixture friction, respectively. Since these frictional forces were not separable from the inertia forces measured in the test program, a trial-and-error method of including these forces had to be employed in the analytical simulation.

Results and Discussion

To validate the AGFATL computer program for predicting the loads and motions of aircraft with conventional passive gears and/or series-hydraulic active control gears, analytical results are compared with data from shaker tests, drop tests, and landing tests of a modified single main gear from a general aviation airplane.

Shaker Tests

In figure 5, time histories of drop-tower-bucket mass acceleration and strut stroke from the shaker tests are compared with those computed with the AGFATL program.

Passive gear response to excitation near resonant frequency. Figure 5(a) compares experimental and analytical acceleration responses of drop-tower-bucket mass to a forcing frequency near the 1.25-Hz strut resonant frequency. The applied forcing function was a 1.3-Hz, 2-in-double-amplitude, five-cycle sinusoidal waveform. Negative acceleration represents upward loads on the mass from the gear. The circled numerals are compressive peaks of the five cycles of excitation. After the third cycle of excitation, the experimental accelerations have reached limit values of approximately $-2.25g$ and $1g$. The value of $-2.25g$ is attributed to a force from a snubber employed in the gear to prevent damage at compression bottoming. The $1g$ limit occurs as the gear fully extends and the tire leaves the shaker table. The analytical accelerations increased throughout the excitation cycles and for one cycle beyond excitation but did not reach a limit, probably because the snubber force was not simulated in the analysis. However, the computed accelerations did reach the $1g$ limit after the third excitation cycle.

Subsequent to the five excitation cycles, the experimental data show that the limit accelerations continue for approximately two cycles before appreciable damping occurs. The computed data show that the resonant effect continues for approximately one cycle before damping is evident. The experimental data also exhibit greater damping than that which occurs with the computed data.

Experimental and analytical strut strokes resulting from the same five cycles of excitation are shown in figure 5(b). Zero stroke is the static stroke of the gear (approximately 5 in.) required to support the mass of the drop-tower bucket. The effect of resonance is again very graphically illustrated by both the experimental and computed data. After approximately two excitation cycles, the experimental data show that the strut is stroking between the limits of maximum compression (influenced by the snubber) and maximum extension (5-in. negative stroke). The computed strokes do not reach a compressive limit but increase during the five excitation cycles; however, on the third excitation cycle, the gear is fully extending (5-in. negative stroke). For two cycles following the excitation, the experimental data show that the gear continues to stroke between the limits of maximum compression and maximum extension before damping occurs. On the other hand, the computed compressive strokes increased for one cycle and continued to fully extend for two cycles before damping reduced the strut stroke.

The higher-than-computed negative experimental accelerations were attributed to the greater experimental compressive strokes (fig. 5(b)), which generated a snubber force that was not simulated in the analysis. Furthermore, the larger experimental compressive strokes probably resulted from friction between the drop-tower bucket and the guide rails that also was not simulated in the analysis. In spite of these differences, the analytical simulation very graphically illustrates the gear response to excitation near gear resonance, and the computed and experimental response data are in good agreement.

Active gear response to excitation near resonant frequency. Experimental and analytical accelerations of the bucket mass are presented in figure 5(c) for the active gear response to an excitation frequency near gear resonant frequency. The five cycles of the forcing function are indicated by the circled numerals. The most obvious characteristic of these data relative to the passive gear data (fig. 5(b)) is the absence of any resonant effect. The experimental and analytical accelerations for the active gear are limited to approximately $0.1g$ and $0.2g$, respectively. Following the excitation, the experimental response is rapidly attenuated, and as was the case with the passive gear, the damping present in the experiment was greater than that analytically simulated.

For the active gear, experimental and analytical strut strokes resulting from the five-cycle, 1.3-Hz, 2-in-double-amplitude excitation are shown in figure 5(d). The five excitation cycles of the forcing function are indicated by the circled numerals. The resonant buildup in response which occurred with the passive gear is absent, and the rapid attenuation of strut response after the last excitation cycle is obvious for both the experimental and analytical strokes, although the analytical data indicate less damping. The experimental compressive strut strokes are generally greater than the analytical simulation, and conversely, the experimental strokes during gear extension are less than the analytical extension strokes. The forces applied to the drop-tower bucket by the active gear are small, and friction between the bucket and guide rails could be a dominant factor. For example, if the friction force was large relative to the gear force, the displacement of the bucket would be smaller and the gear would stroke more. Also, if the displacement of the upper mass was restrained during the compressive stroke of the gear, gear extension would be restrained by the shaker table displacement. The experimental data indicate that this may have been the case; however, no bucket displacement data were presented in reference 14 to substantiate this behavior. Friction between the drop-tower bucket and guide rails was not simulated in the analysis, and the bucket was unrestrained in vertical motion. Therefore, during compressive stroking of the gear, the bucket would displace more and hence reduce the gear stroke. Conversely, because of the greater bucket displacement, the gear would extend to a greater stroke even though it was restrained by the shaker table displacement.

Both the experimental and analytical active gear responses to five cycles of excitation demonstrate the effectiveness of the active gear in eliminating gear resonant response. Excellent agreement was noted between the experimental and computed accelerations of the bucket mass. Although the agreement between experimental and computed strut strokes was not as good, the high probability of friction existing between the drop-tower bucket and guide rails makes the disparity less significant.

Passive gear response to 2.5-in. step bump. Figure 5(e) presents experimental and analytical drop-tower-bucket mass accelerations resulting from the response of the passive gear to a 2.5-in-high step bump. The experimental acceleration is greater than the analytical during the step-up, the rebound, and the compressive portion of the first oscillation. The damping in the experimental test apparatus was greater than the damping in the analysis, as evidenced by the fact that the experimental acceleration had dropped to zero at a time of about 6 seconds, but the computed acceleration was still oscillating. Even though the analytical acceleration was lower than the experimental in response to the step-up and the first oscillation, the character of the response was the same.

For the step-down input, the analytical acceleration was greater than the experimental because the computed acceleration was still oscillating from the step-up input, but the experimental acceleration had damped to zero. During the first rebound oscillation, the experimental acceleration was again greater than the computed, but following the step inputs, the magnitude and the frequency of oscillation (1.3 Hz) was the same for both the experimental and computed data.

Passive gear experimental and analytical strut strokes in response to a 2.5-in-high step bump are shown in figure 5(f). The experimental strut stroke during the step-up input and strut extension during rebound were greater than those predicted by the analysis. As previously discussed, the friction force between the drop-tower bucket and guide rails could result in greater strokes than would occur with the unrestrained vertical motion in the analytical simulation. The same hypothesis would apply to the strut stroke response to the step-down input.

The maximum experimental and analytical accelerations are different during the step-up input, rebound, and compressive portion of the first oscillation; however, the character of the accelerations is the same.

The experimental and analytical strut strokes are different, but the presence of friction between the drop-tower bucket and guide rails during the experiment may account for the difference.

Active gear response to 2.5-in. step bump. The experimental and analytical drop-tower-bucket accelerations for the active gear are shown in figure 5(g) for response to a 2.5-in-high step bump. The agreement between experimental and computed accelerations for the step inputs is excellent. However, as has been the case for all the shaker tests, the damping in the test apparatus is greater than that used in the analysis.

Figure 5(h) presents experimental and analytical shock-strut strokes for the active gear when subjected to a 2.5-in-high step bump. The experimental strokes are greater than the computed strokes, and following the step-up and step-down inputs, the experimental static stroke is biased relative to the designed static stroke to a greater compressive stroke. Following the step-down input, the experimental stroke data quickly return to the biased static stroke, but the computed stroke requires a greater time to return to the static stroke. These discrepancies may result from the frictional effects previously discussed, deviation in shaker performance, or differences in the response of the analytically simulated controller relative to those which occurred in the experiment.

The agreement between experimental and analytical accelerations of the drop-tower bucket in response to the 2.5-in. step bump was excellent. The agreement between experimental and computed strut strokes was not as good, but the trend of the stroke data in response to the step-up input was the same. The reason for the difference between the strokes following the step-down input is not understood.

In summary, the agreement between experimental and analytical data obtained for the shaker tests of the passive and active gears was good despite some differences, which may be attributed to snubber or frictional forces in the experimental apparatus that were not represented in the analytical simulation.

Drop Tests

Comparisons of experimental and analytical results obtained for vertical-drop tests of the passive and active gears are shown in figure 6 for a ground speed of zero, a sink rate of 5.5 fps, and a pitch attitude of 0°. The strut-binding friction is a minimum for these touchdown parameters. However, friction forces were present between the drop frame and the standoff structure used in the experimental investigation of reference 14. The tests analytically simulated for the passive and active gears were tests 49 and 51, respectively.

Drop test of passive gear. The experimental and analytical mass-center forces and shock-strut strokes for the vertical-drop test of the passive gear are shown in figure 6(a). The computed mass-center forces and strut strokes are in good agreement with the experimental data during touchdown impact, rebound, and secondary impact. Experimental and computed strut-hydraulic pressures shown in figure 6(b) are in good agreement during touchdown impact and rebound. During secondary impact and damping to static pressure, the experimental pressures were generally higher than the computed values.

Drop test of active gear. Figure 6(c) presents comparisons between experimental and analytical mass-center forces and shock-strut strokes for the active gear drop test. The agreement between the experimental and analytical mass-center forces is good. The agreement between the experimental and analytical shock-strut strokes is good during touchdown impact and rebound, but the maximum computed stroke is greater than the experimental stroke during secondary impact and damping to static deflection. This difference may be caused by the relatively small differences in magnitude and timing of the forces which occurred during the touchdown impact and rebound phases of the simulation.

Experimental and analytical strut-hydraulic pressures and servo-spool displacements are shown in figure 6(d) for the active gear drop test. The general trends of the experimental and computed pressures and servo-spool displacements are in good agreement. However, the maximum value of the computed pressure is greater than the experimental pressure during touchdown impact and is less than the experimental pressure during rebound. These discrepancies may be attributed to small differences between response of the servovalve used in the experimental program and that simulated in the analysis. For example, the computed servovalve displacement had greater positive and negative values during rebound than those which occurred during the experiment.

In summary, although there are differences between the experimental and analytical data obtained from the drop tests of the active gear, the agreement between experimental and analytical data is good.

Landing Tests

Comparisons of experimental and analytical results for landing-simulation tests of the passive and active gears are shown in figure 7. The tests were conducted for a ground speed of 80 knots, a touchdown sink rate of 5.5 fps, and a pitch attitude of 2°. The analytical simulations for the passive and active gears are tests 40 and 42 of reference 15, respectively. The inclusion of friction forces in the analytical simulations of these tests was a very difficult task, since these forces were not specifically defined during the test program. In addition, the strut-binding friction, which was of considerable magnitude as evidenced by the fact that the strut would stop stroking during the period of maximum stroking velocity, had to be applied in conjunction with the friction forces of the test fixture and the moments from the elevator control and nose-gear force simulators. As a result, these forces and moments had to be staged into the program by a trial-and-error method.

Landing test of passive gear. Figure 7(a) compares experimental and analytical mass-center forces and shock-strut strokes for the touchdown impact phase of the landing. The agreement between the experimental and analytical mass-center forces was excellent. The agreement between experimental and computed shock-strut strokes was not as good, but the characteristic shape of the analytical data was the same as that of the experimental data. The differences between stroke data resulted from the difficulty of introducing the proper proportions of strut-binding and test fixture friction forces and elevator control and nose-gear moments. Additional factors, which influence the strokes during the latter stages of the computed time history, are small errors in simulating forces and moments during the initial impact phase, which result in cumulative errors during subsequent portions of the time history. This is indicated by the differences in strut strokes during secondary impact and transition to static stroke. Despite the unusually large friction forces encountered with this gear during the experiment and the related difficulties encountered during the analytical simulation, the computed data represent the dynamics of the system very well during the touchdown impact phase of the landing.

Experimental and analytical mass-center forces and shock-strut strokes for the passive gear during traverse of the step bumps are shown in figure 7(b). The force and stroke time histories are plotted from an arbitrarily selected time (zero time in the figure) before encounter with the first bump through traverse of the second bump. Since the gear was stroked to the static position prior to encounter with the bumps and the gear-bearing spacing was greater, the strut-binding friction force was much smaller than that which occurred during the touchdown impact phase. The friction force between the drop frame and the standoff structure was still present and presumably of similar magnitude. No attempt was made to analytically simulate friction forces due to gear wear or test fixture during traverse of the bumps. Although the computed mass-center forces, both positive and negative, were greater than the experimental values during the bump encounters, the general shapes of the experimental and computed force time histories were the same. The incremental changes in the experimental and computed shock-strut strokes and the shapes of the stroke time histories were the same. Although no attempt was made to simulate strut-binding and test fixture friction forces, the agreement between mass-center forces and shock-strut strokes for the passive gear was good during traverse of the step bumps.

Landing test of active gear. For the active gear, figure 7(c) compares experimental and analytical mass-center forces and shock-strut strokes, and figure 7(d) compares strut-hydraulic pressures and servo-spool displacements. The experimental and computed forces, strokes, pressures, and servo-spool displacements were in good agreement during the compressive phase of the initial impact, with slightly less agreement during the rebound phase. The experimental stroke data during rebound indicate that large cyclic frictional forces (side-by-side symbols) were generated which were not analytically simulated. Consequently, the gear extends at a greater rate analytically than it did experimentally, produces an earlier transition of the servo-spool displacement from removing fluid to adding fluid, and results in a greater analytical shock-strut pressure. These differences during rebound resulted in greater differences between the experimental and analytical data during secondary impact and transition to the static stroke.

Despite the difficulties with analytically simulating friction forces, the agreement between experimental and computed data during the compressive phase of the initial impact was good. As a result of the inability to analytically simulate the strut friction during the rebound phase of the initial impact, particularly for the active gear in which the servovalve control responds to force fluctuations, only fair agreement was obtained between experimental and analytical data during rebound, secondary impact, and transition to static stroke.

Concluding Remarks

A computer program for multi-degree-of-freedom active gear, flexible aircraft take-off and landing analysis (AGFATL) was developed for studying series-hydraulic active gears. To validate the AGFATL computer program for predicting the loads and motions of aircraft with conventional passive gears and/or series-hydraulic active control gears, analytical results are compared with data obtained from shaker tests, drop tests, and landing tests of a modified single main gear from a general aviation airplane.

Comparison of experimental and analytical responses for both passive and active gears indicates good agreement for shaker tests (forced vibrations) and drop tests (although there were some differences). For the simulated-landing tests, the passive and active gears were influenced by large strut-binding friction forces. The inclusion of these undefined forces in the analytical simulations was difficult, particularly for the active gear in which the servovalve control responds to force fluctuations; consequently, only fair to good agreement was obtained between experimental and analytical responses for the landing tests.

An overall assessment of the results from the investigation indicates that (despite the susceptibility to frictional forces of the gear employed in this investigation) the AGFATL computer program is a valid tool for the study and initial design of series-hydraulic active control landing-gear systems.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
July 13, 1984

References

1. DC-10 Landing Gear Modified. *Aviat. Week & Space Technol.*, vol. 98, no. 12, Mar. 19, 1973, p. 181.
2. Ropelewski, Robert R.: Airbus Test Tempo Quickening. *Aviat. Week & Space Technol.*, vol. 98, no. 10, Mar. 5, 1973, pp. 32–35.
3. Wignot, Jack E.; Durup, Paul C.; and Gamon, Max A.: *Design Formulation and Analysis of an Active Landing Gear. Volume I. Analysis.* AFFDL-TR-71-80, Vol. I, U.S. Air Force, Aug. 1971. (Available from DTIC as AD 887 127L.)
4. Bender, E. K.; Berkman, E. F.; and Bieber, M.: *A Feasibility Study of Active Landing Gear.* AFFDL-TR-70-126, U.S. Air Force, July 1971. (Available from DTIC as AD 887 451L.)
5. McGehee, John R.; and Carden, Huey D.: *A Mathematical Model of an Active Control Landing Gear for Load Control During Impact and Roll-Out.* NASA TN D-8080, 1976.
6. Lynch, Urban H. D.: *Takeoff and Landing Analysis (TOLA) Computer Program. Part 1—Capabilities of the Takeoff and Landing Analysis Computer Program.* AFFDL-TR-71-155, Part 1, U.S. Air Force, Feb. 1972. (Available from DTIC as AD 741 942.)
7. Lynch, Urban H. D.; and Dueweke, John J.: *Takeoff and Landing Analysis (TOLA) Computer Program. Part II—Problem Formulation.* AFFDL-TR-71-155, Part II, U.S. Air Force, May 1974.
8. Lynch, Urban H. D.; and Dueweke, John J.: *Takeoff and Landing Analysis Computer Program (TOLA). Part III—User's Manual.* AFFDL-TR-71-155, Part III, U.S. Air Force, Apr. 1974.
9. Young, Fay O.; and Dueweke, John J.: *Takeoff and Landing Analysis Computer Program (TOLA). Part IV—Programmer's Manual.* AFFDL-TR-71-155, Part IV, U.S. Air Force, Jan. 1975.
10. Dick, J. W.; and Benda, B. J.: *Addition of Flexible Body Option to the TOLA Computer Program. Part I—Final Report.* NASA CR-132732-1, 1975.
11. Dick, J. W.; and Benda, B. J.: *Addition of Flexible Body Option to the TOLA Computer Program. Part II—User and Programmer Documentation.* NASA CR-132732-2, 1975.
12. Carden, Huey D.; and McGehee, John R.: *Validation of a Flexible Aircraft Take-Off and Landing Analysis (FATOLA).* NASA TP-1025, 1977.
13. Ross, Irving; and Edson, Ralph: *An Electronic Control for an Electrohydraulic Active Control Aircraft Landing Gear.* NASA CR-3113, 1979.
14. Morris, David L.: *Active Landing Gear Response Testing.* AFWAL-TM-82-177-FIEM, U.S. Air Force, Apr. 1982.
15. McGehee, John R.; and Dreher, Robert C.: *Experimental Investigation of Active Loads Control for Aircraft Landing Gear.* NASA TP-2042, 1982.
16. Mall, Gerald H.: *Improvements to the FATOLA Computer Program Including Added Actively Controlled Landing Gear Subroutines.* NASA CR-166069, 1983.

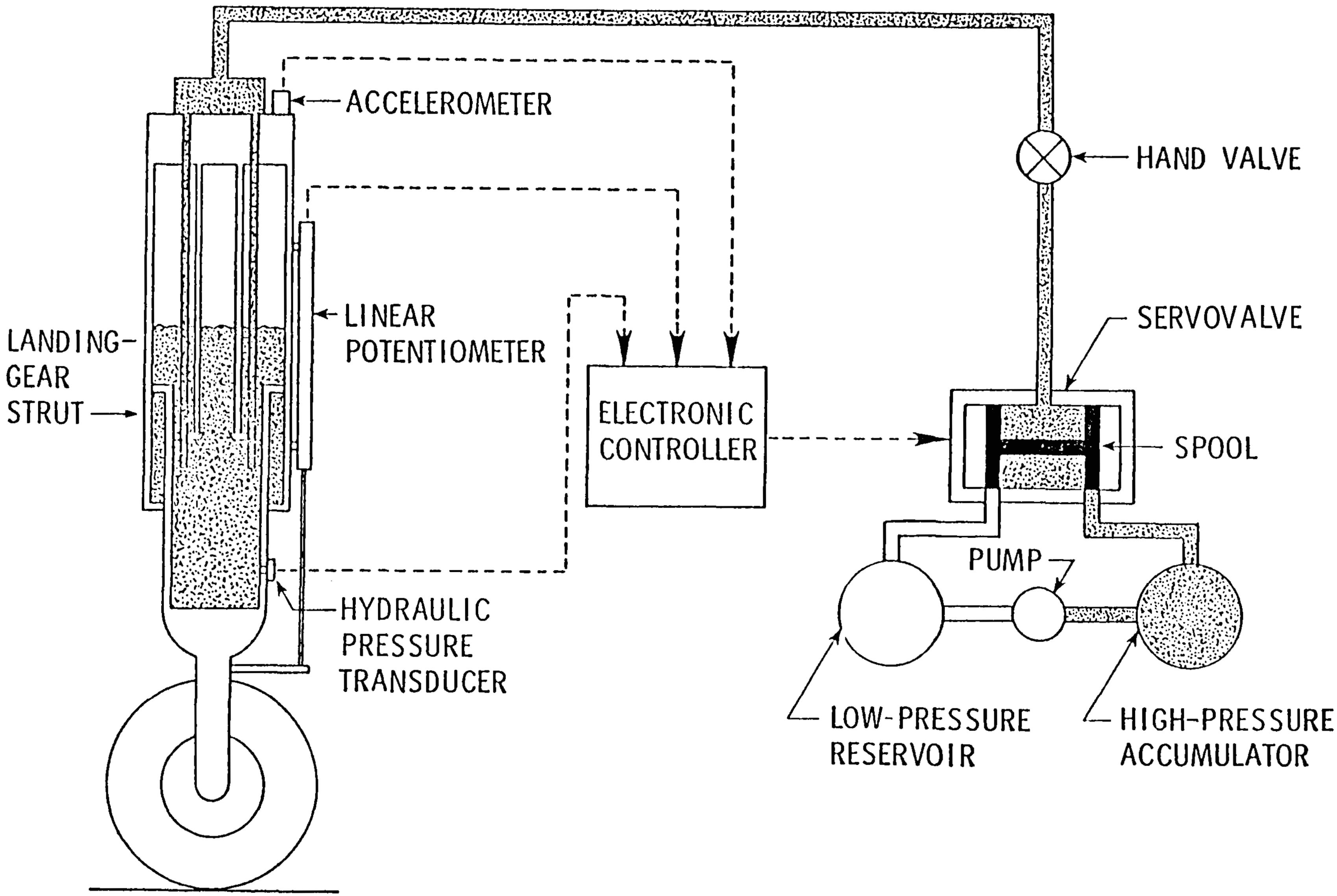
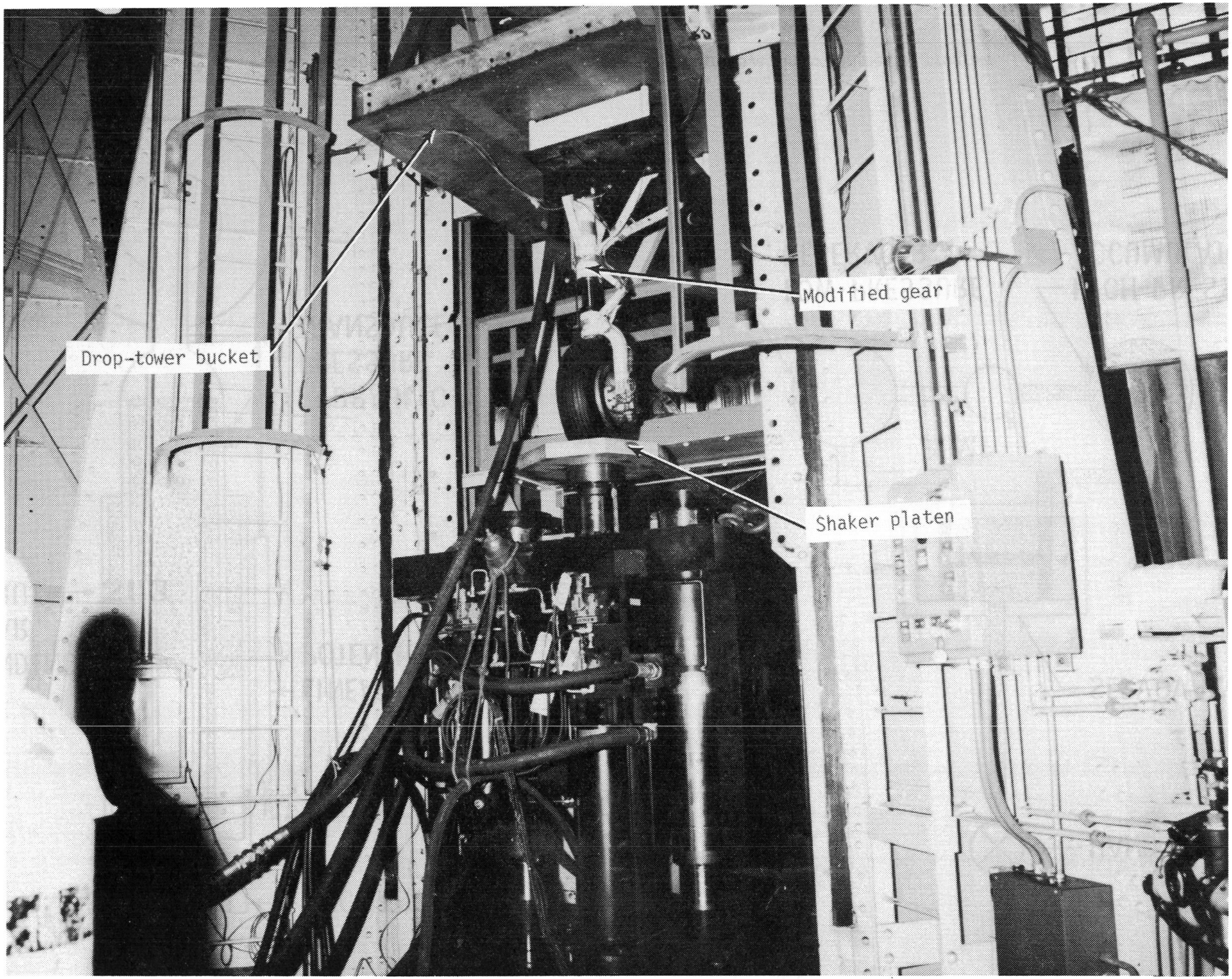


Figure 1. Schematic of active control landing gear employed in experimental program.



L-84-95

Figure 2. Modified active gear mounted for shaker tests.

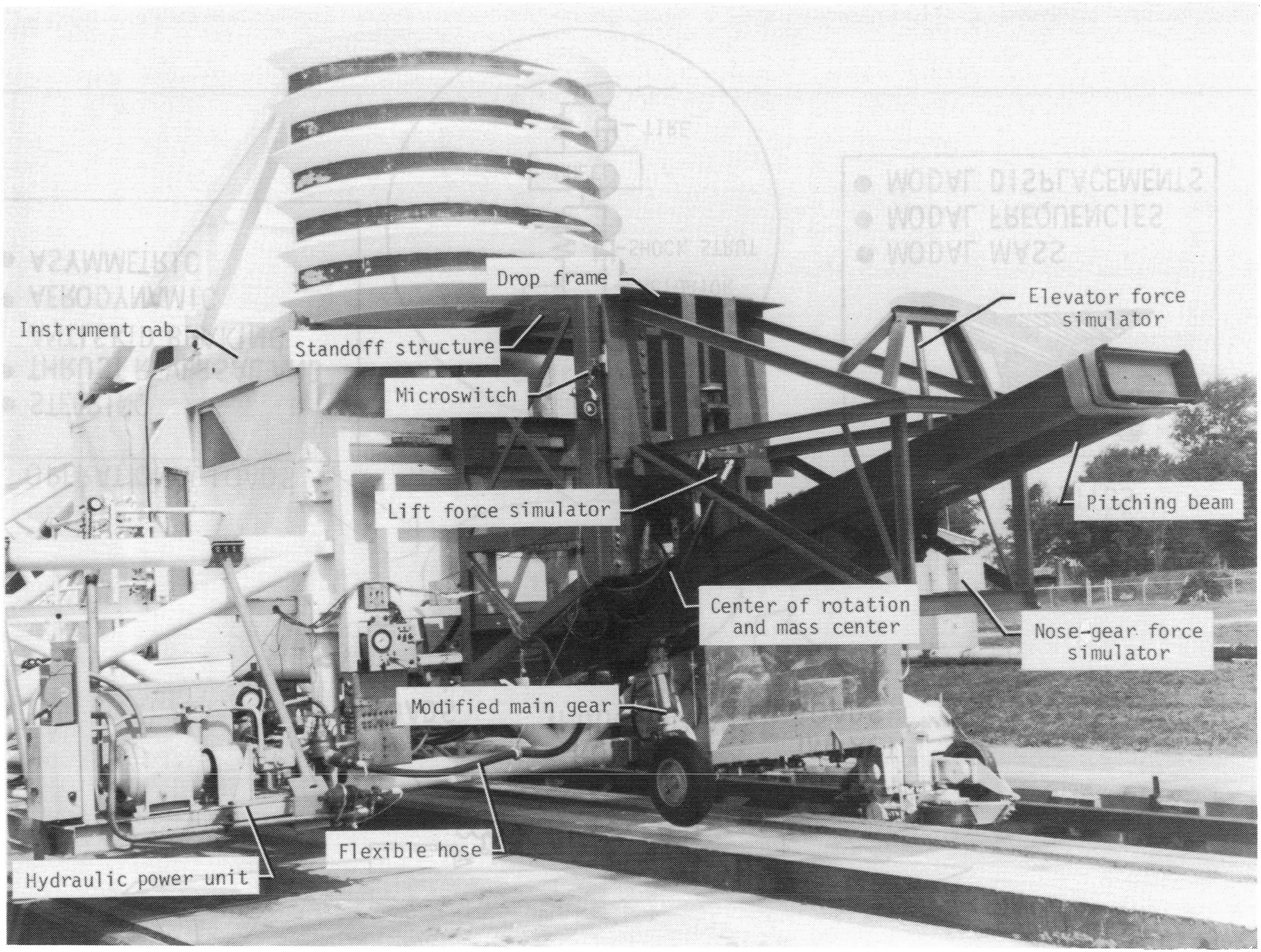


Figure 3. Test equipment and setup for drop and landing tests.

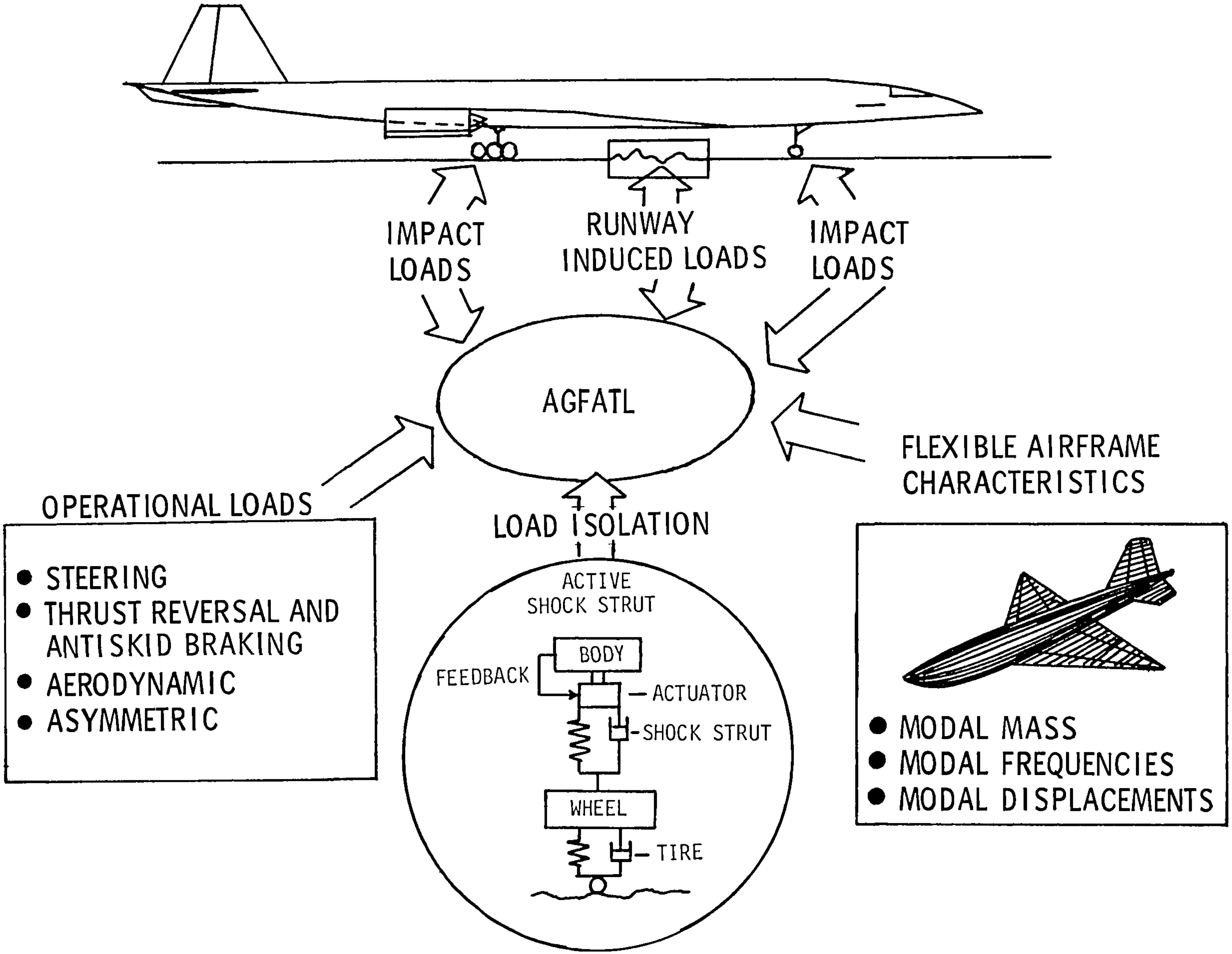
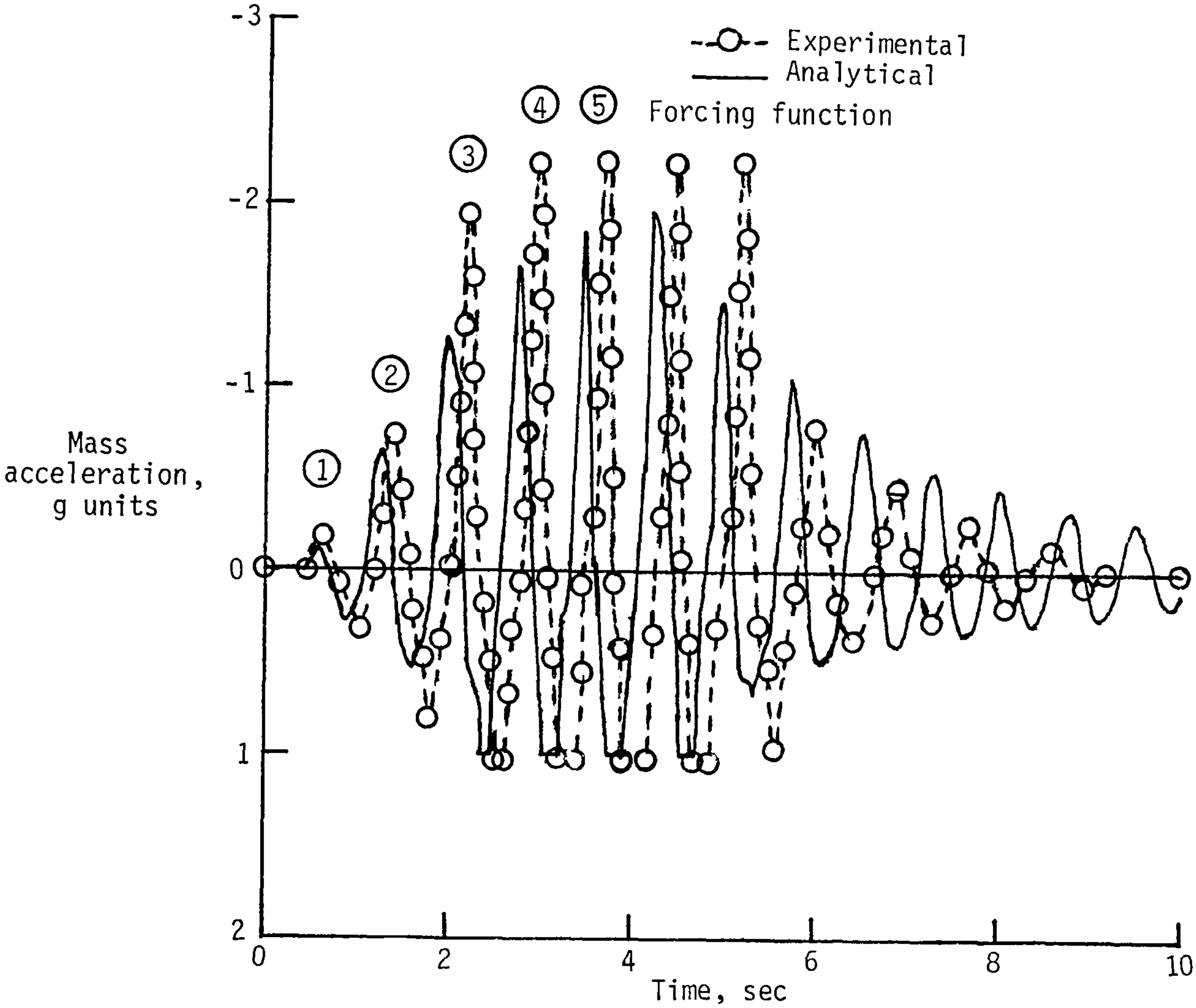
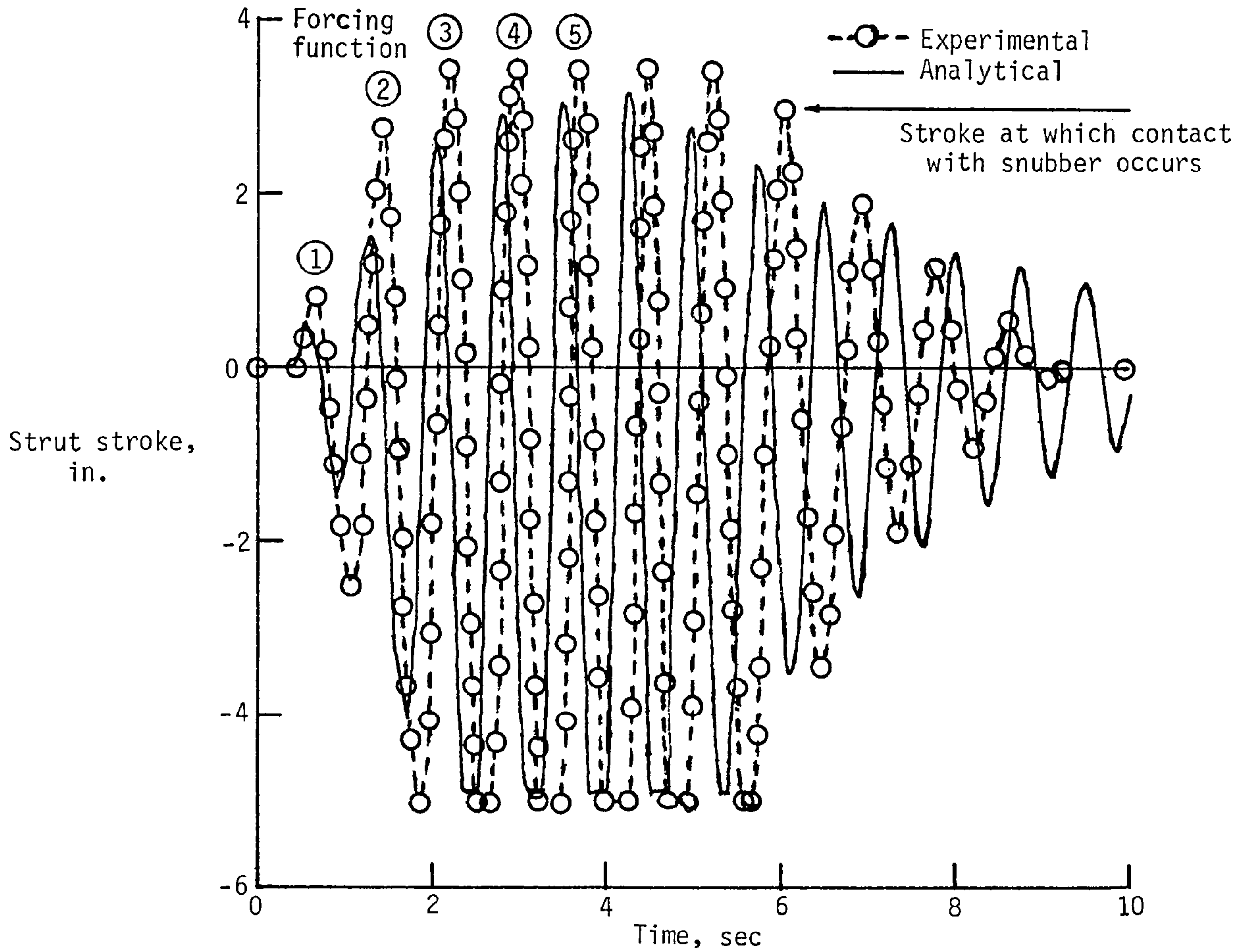


Figure 4. Capabilities of active gear, flexible aircraft take-off and landing analysis.



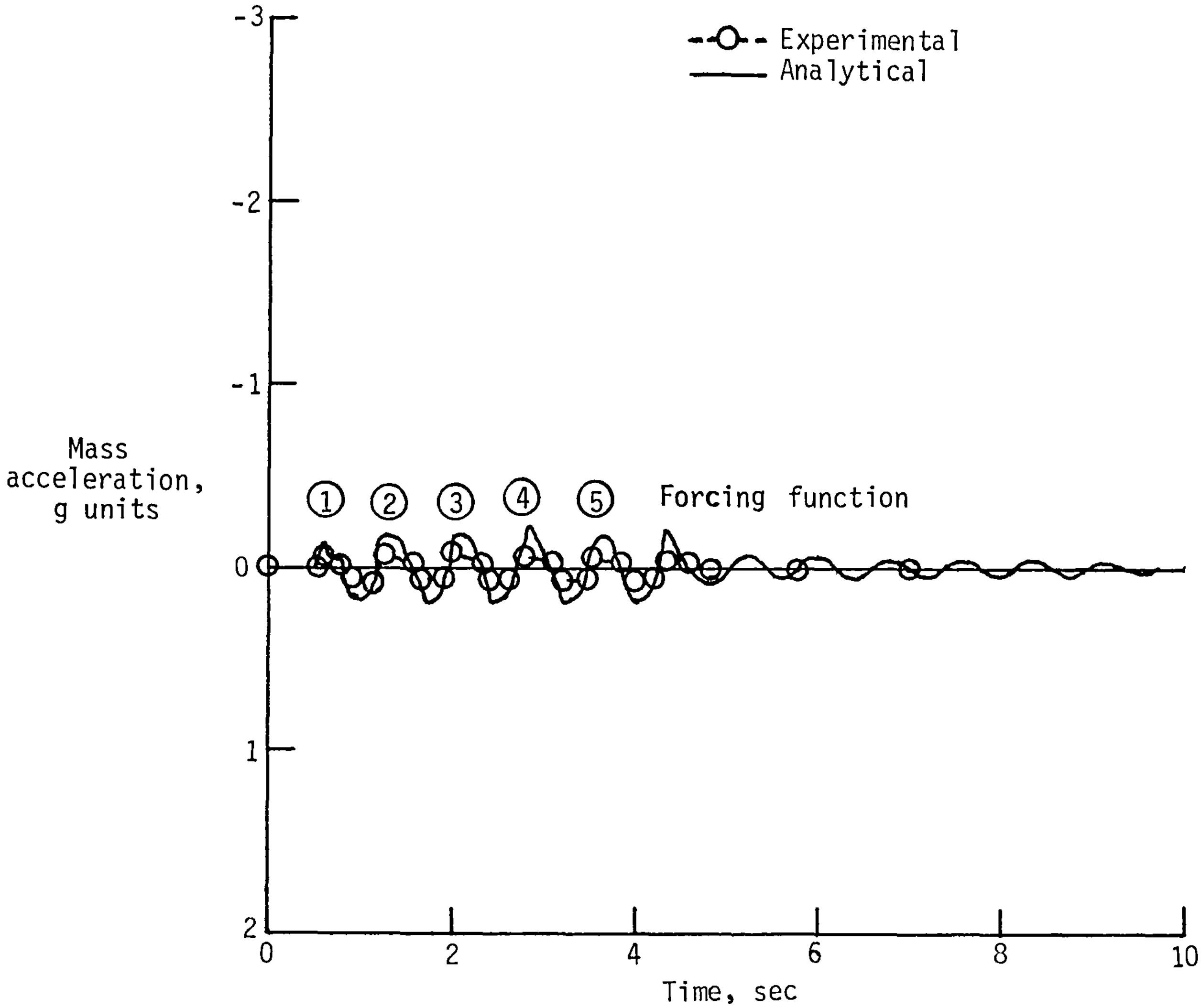
(a) Mass accelerations for passive gear tested at a frequency of 1.3 Hz and a double amplitude of 2 in.

Figure 5. Experimental and analytical results for shaker tests.



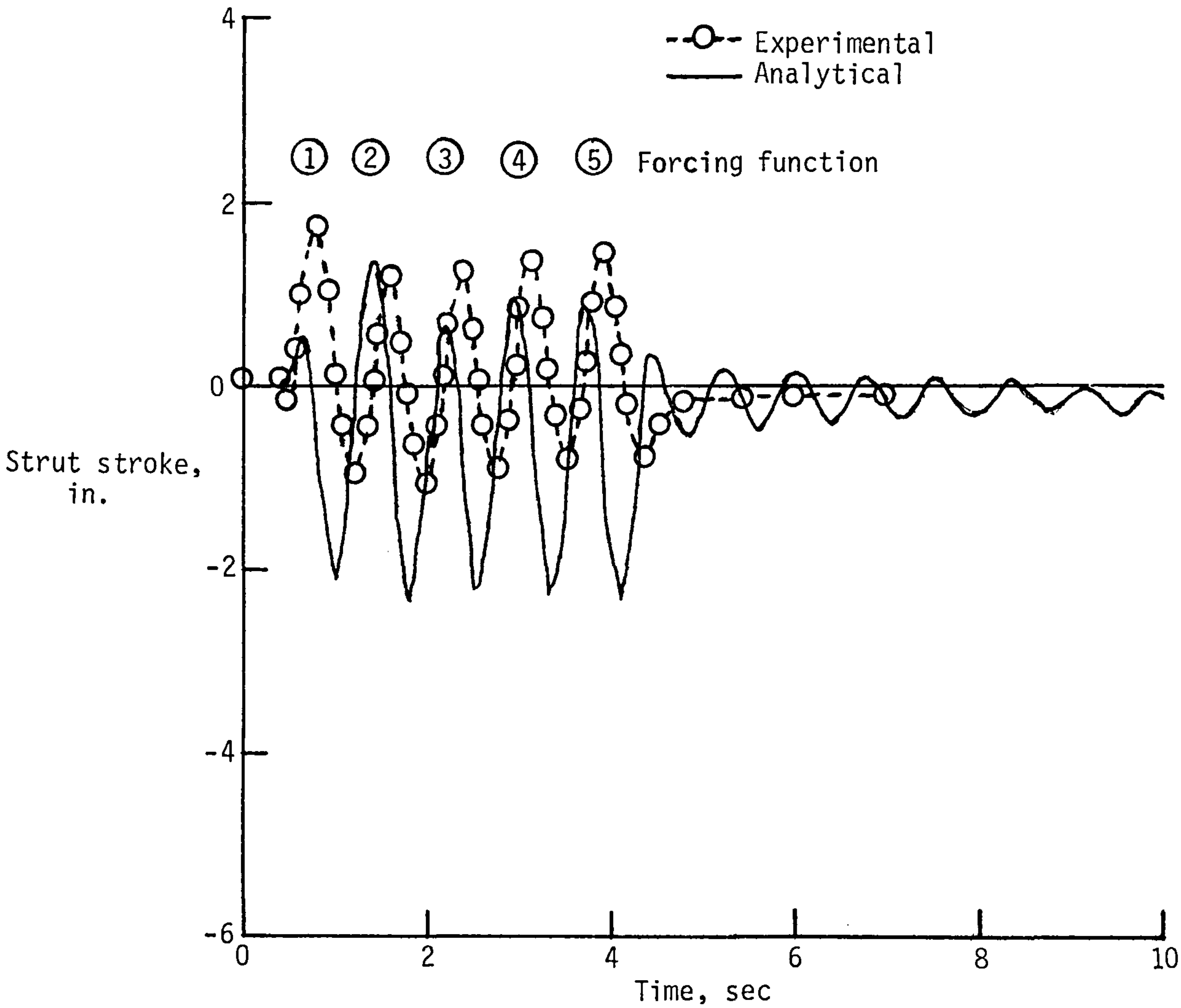
(b) Strut strokes for passive gear tested at a frequency of 1.3 Hz and a double amplitude of 2 in.

Figure 5. Continued.



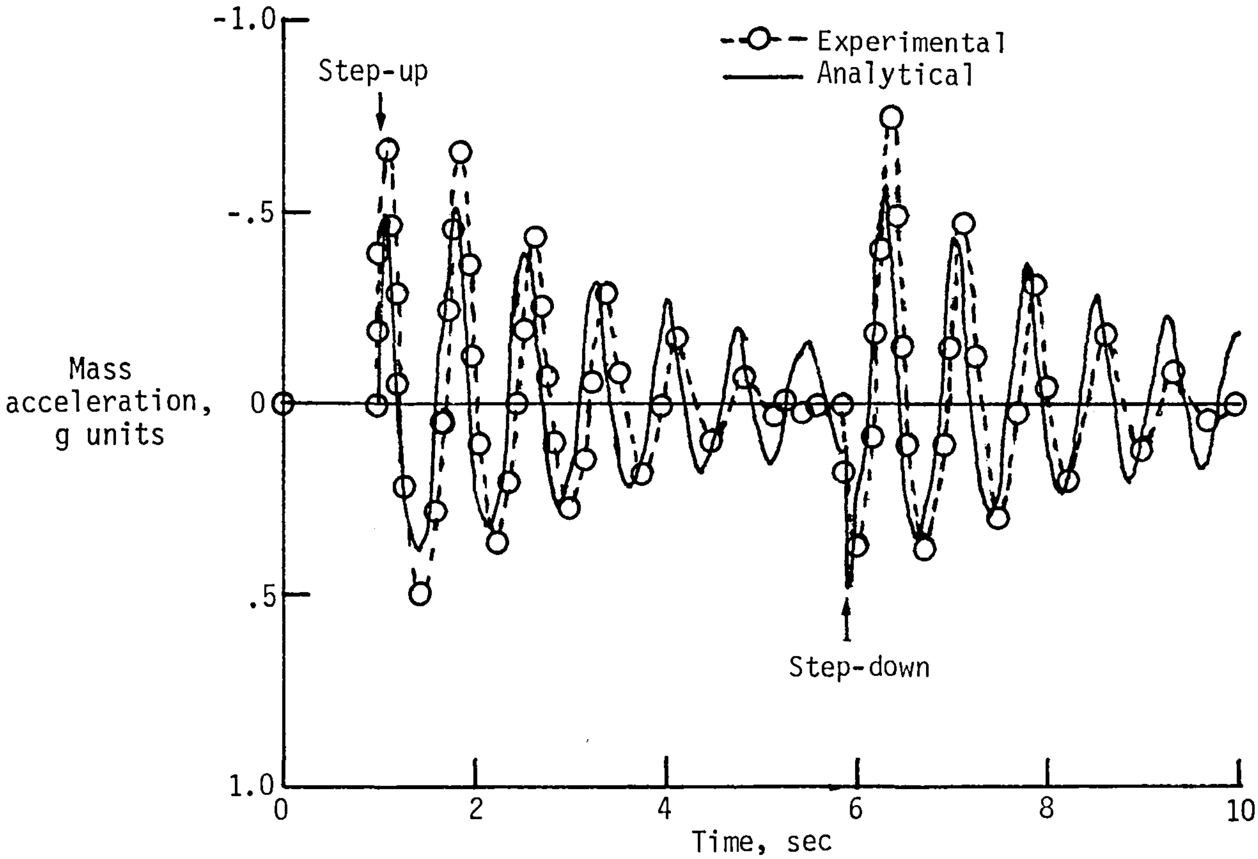
(c) Mass accelerations for active gear tested at a frequency of 1.3 Hz and a double amplitude of 2 in.

Figure 5. Continued.



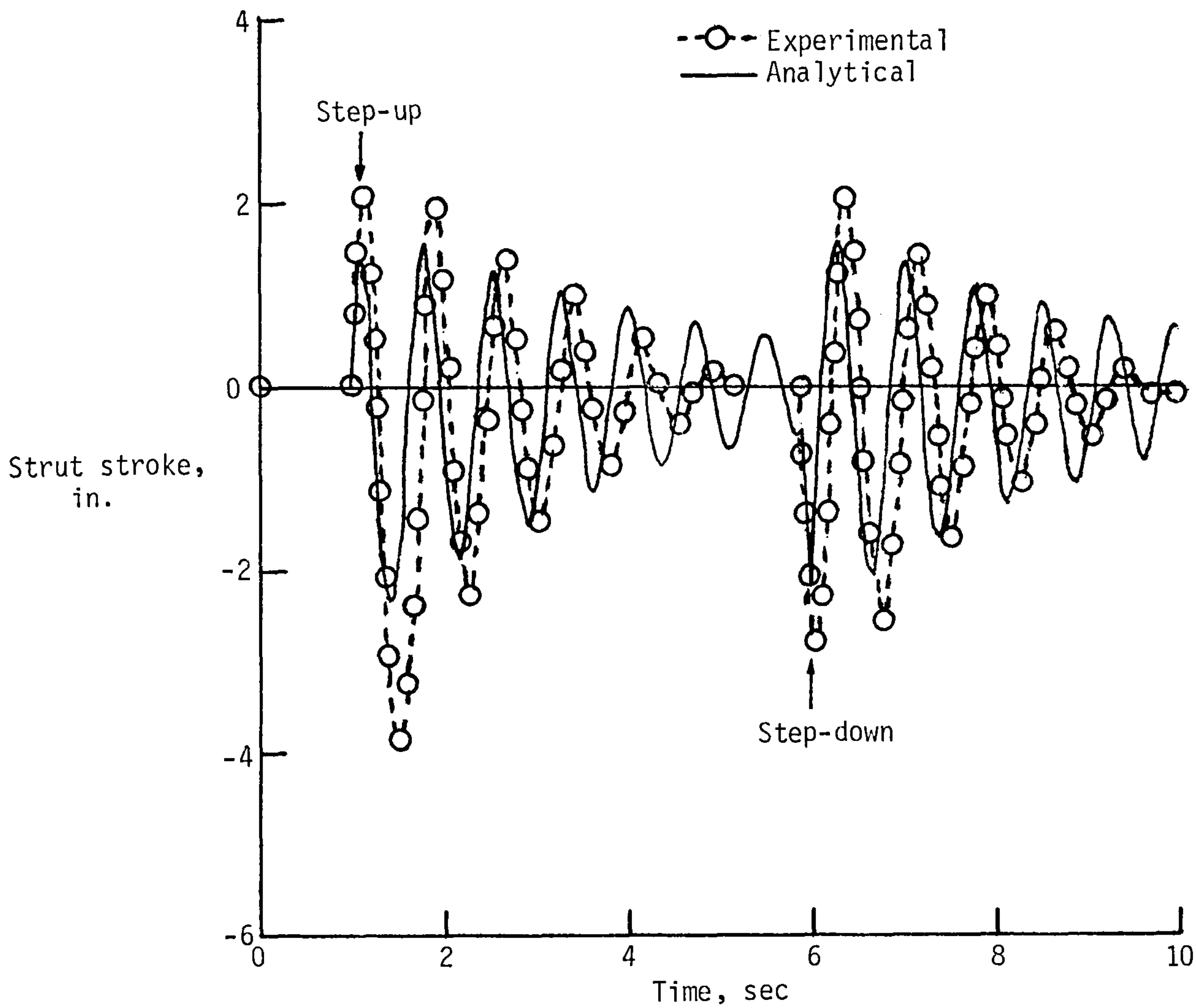
(d) Strut strokes for active gear tested at a frequency of 1.3 Hz and a double amplitude of 2 in.

Figure 5. Continued.



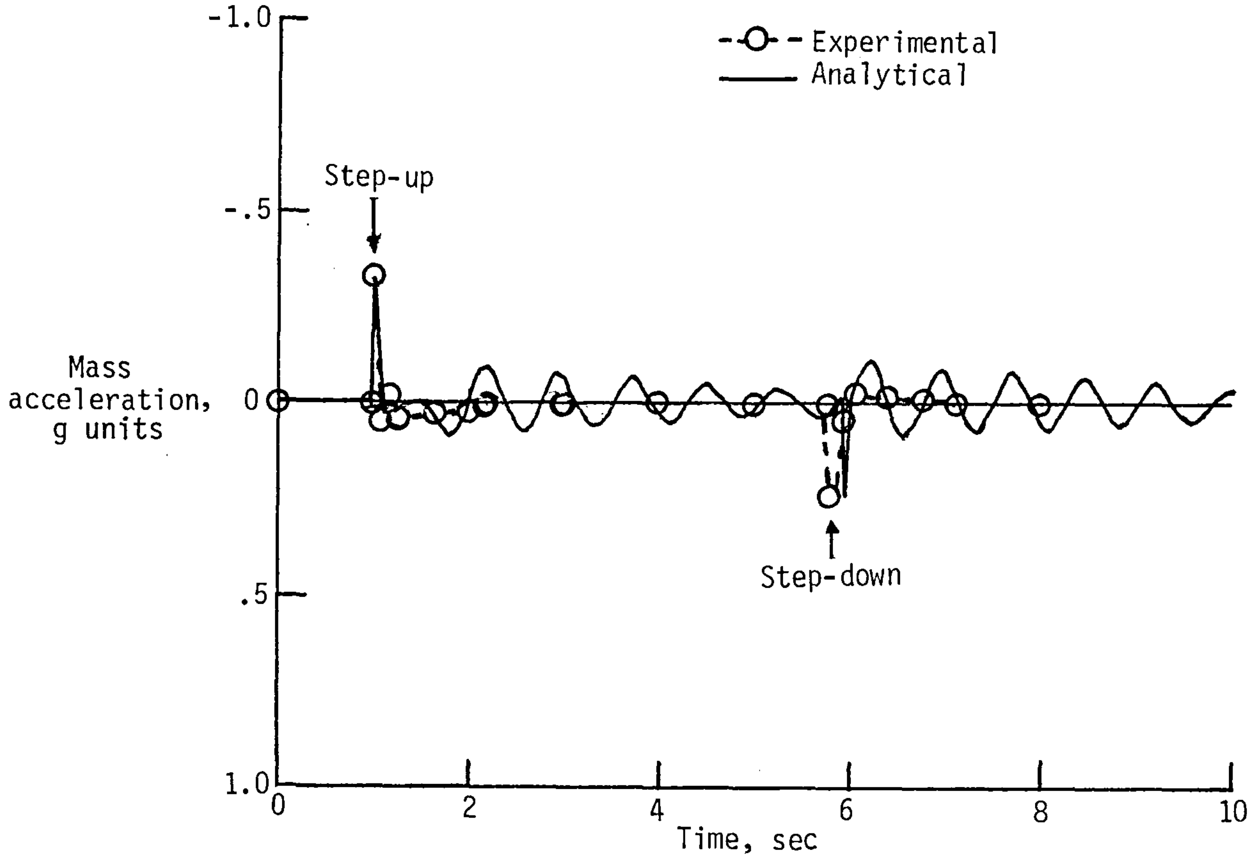
(e) Mass accelerations for passive gear subjected to 2.5-in-high step bump.

Figure 5. Continued.



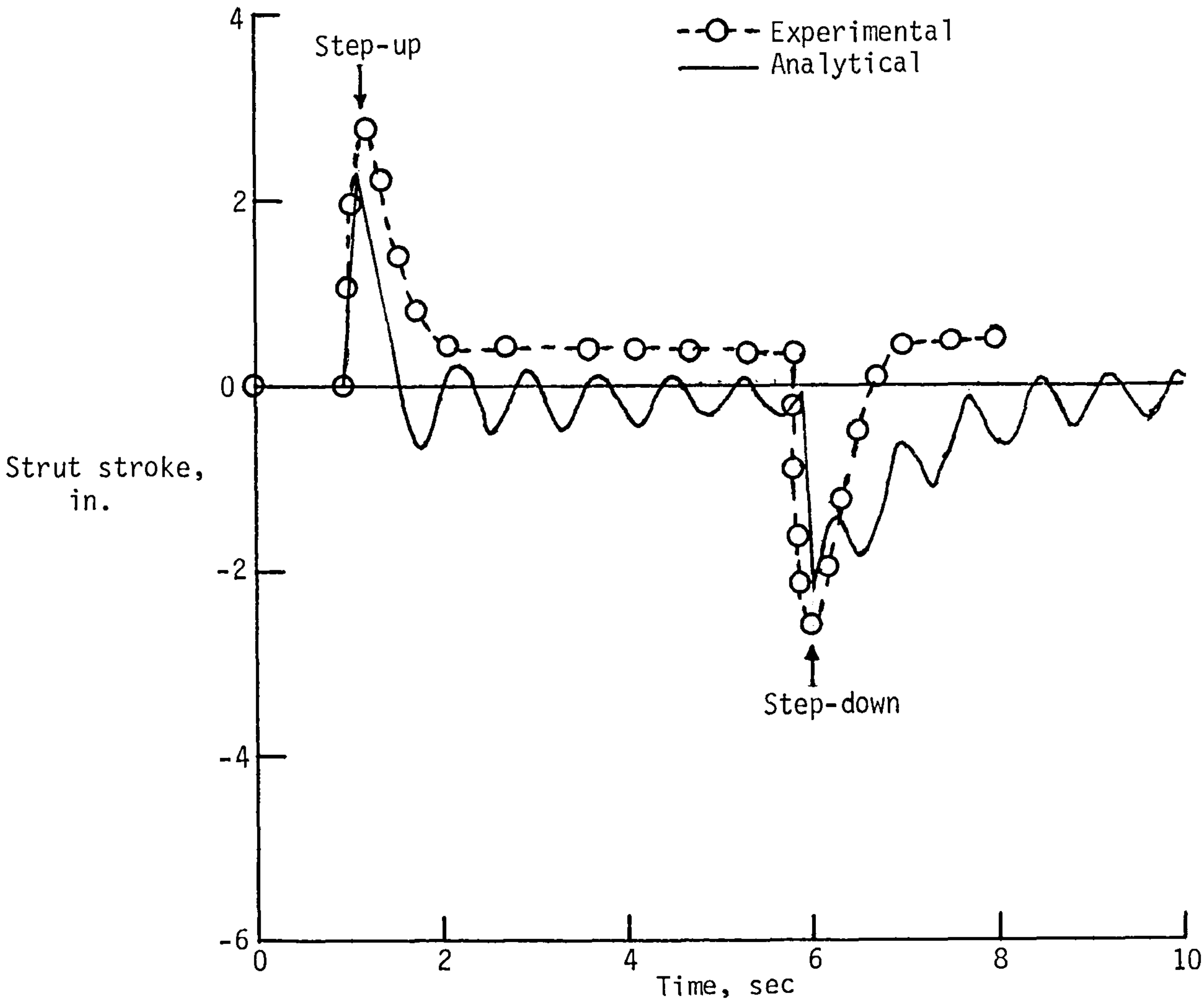
(f) Strut strokes for passive gear subjected to 2.5-in-high step bump.

Figure 5. Continued.



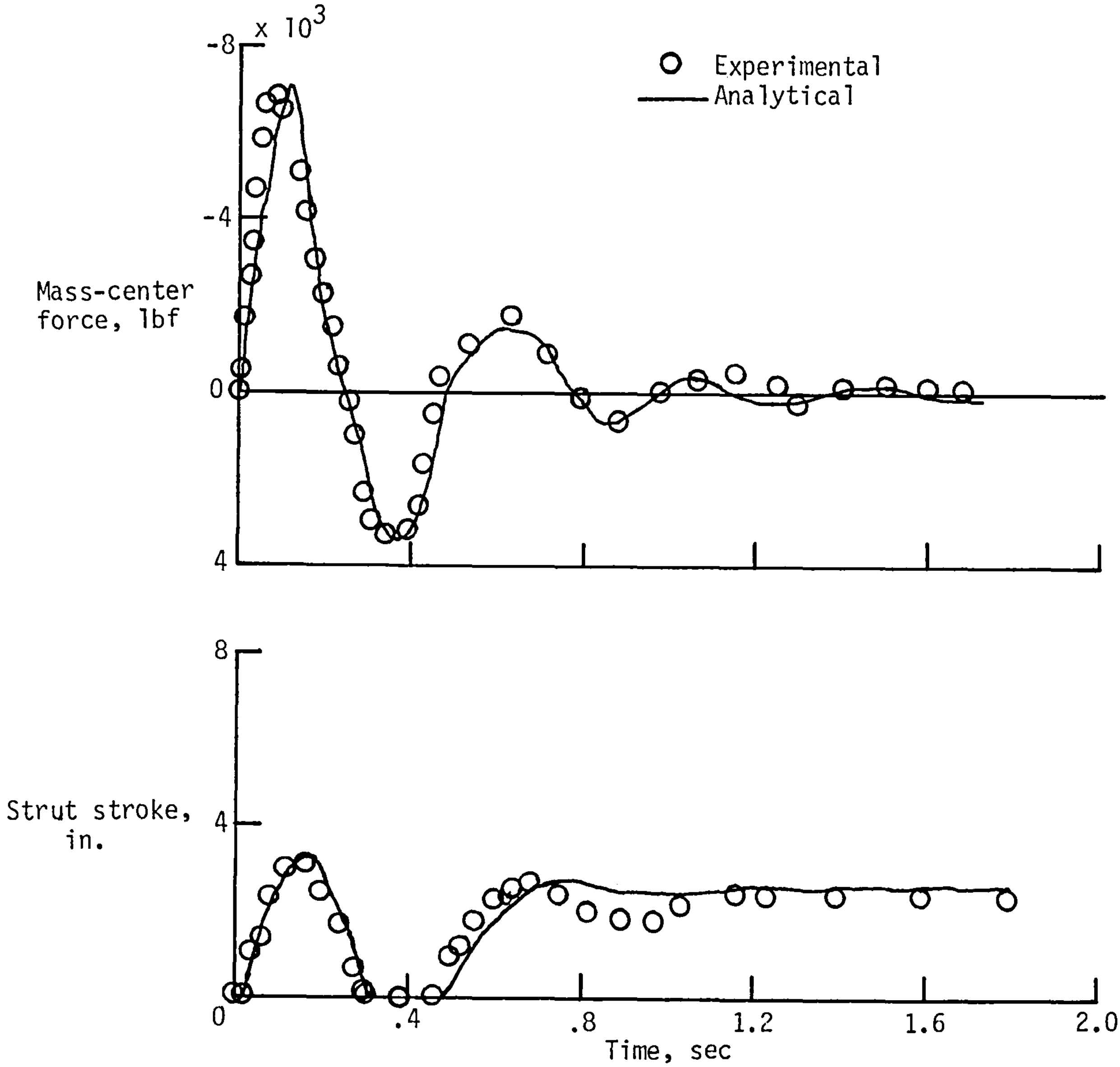
(g) Mass accelerations for active gear subjected to 2.5-in-high step bump.

Figure 5. Continued.



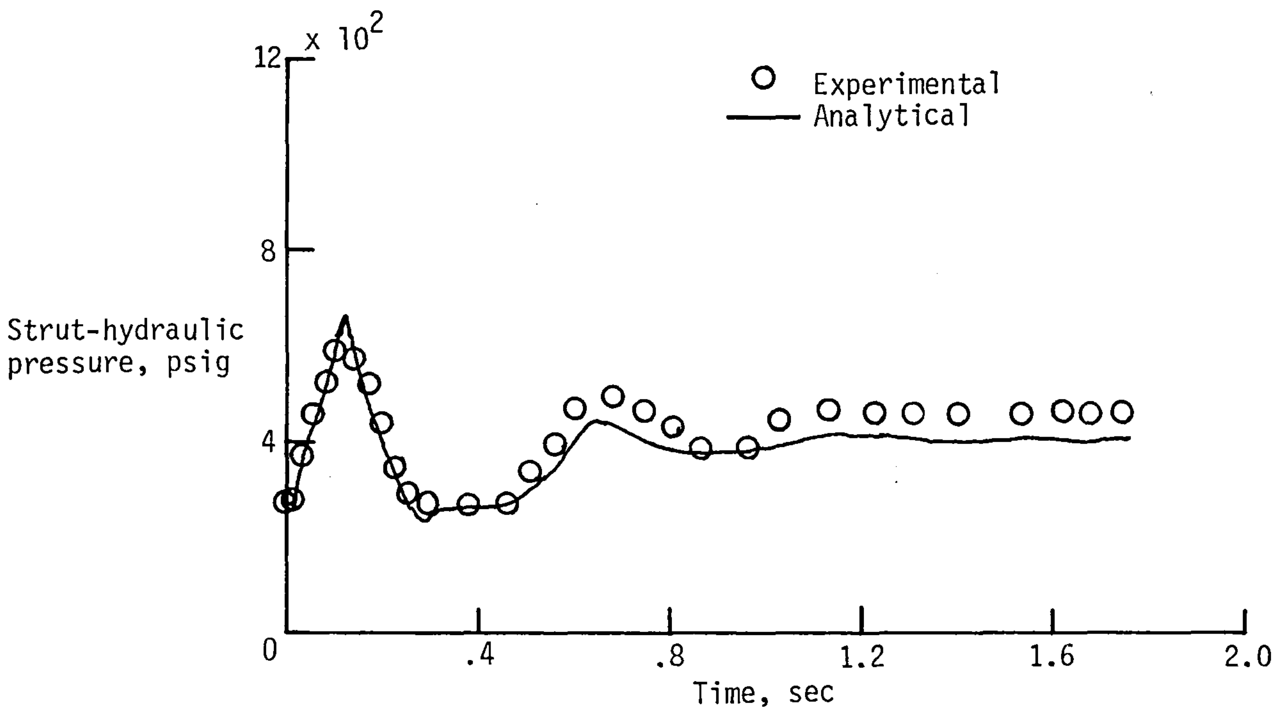
(h) Strut strokes for active gear subjected to 2.5-in-high step bump.

Figure 5. Concluded.



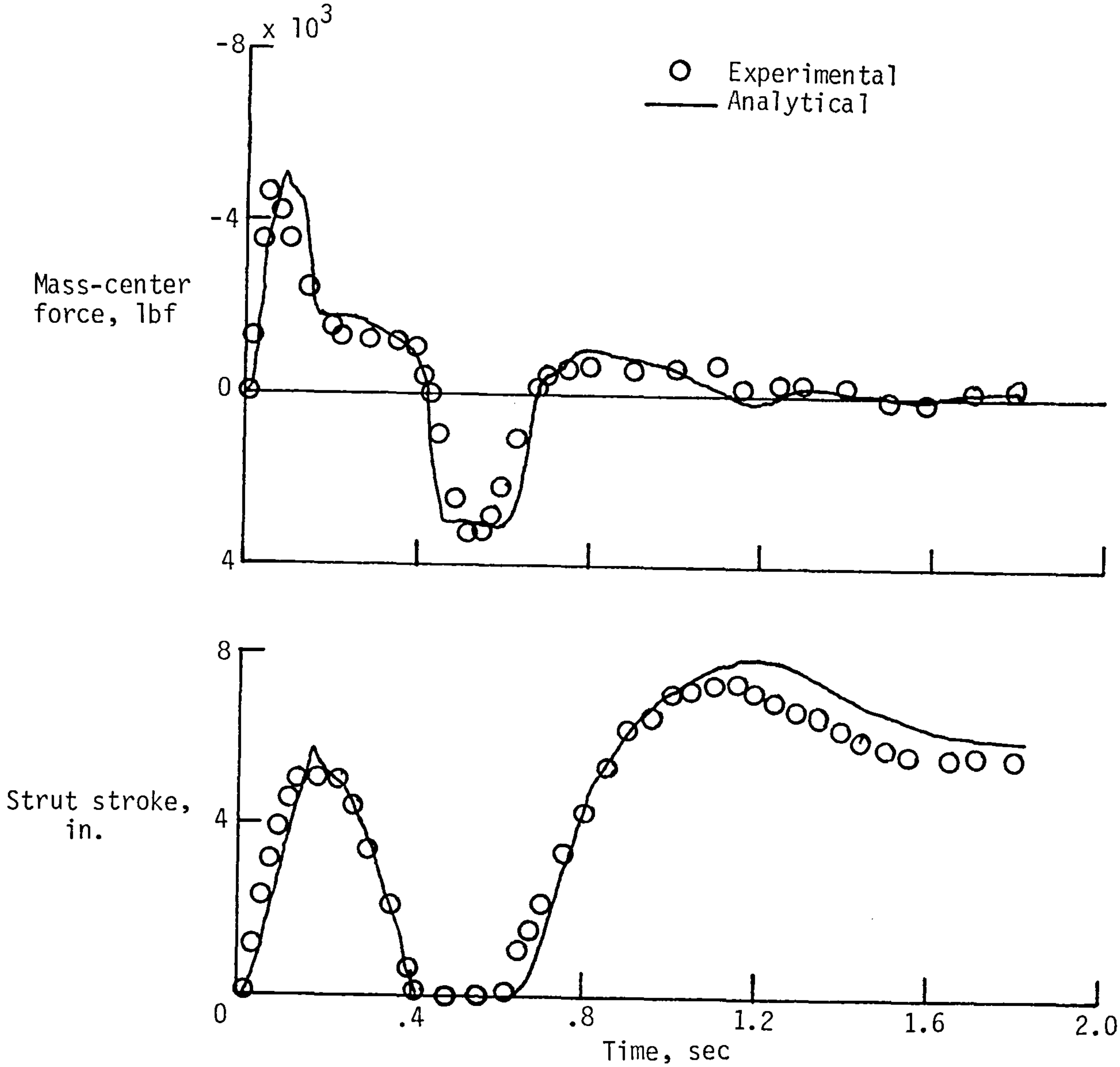
(a) Mass-center forces and shock-strut strokes for passive gear. Test 49 of reference 14.

Figure 6. Experimental and analytical results from vertical-drop tests. Ground speed, 0 knots; touchdown sink rate, 5.5 fps; pitch attitude, 0°.



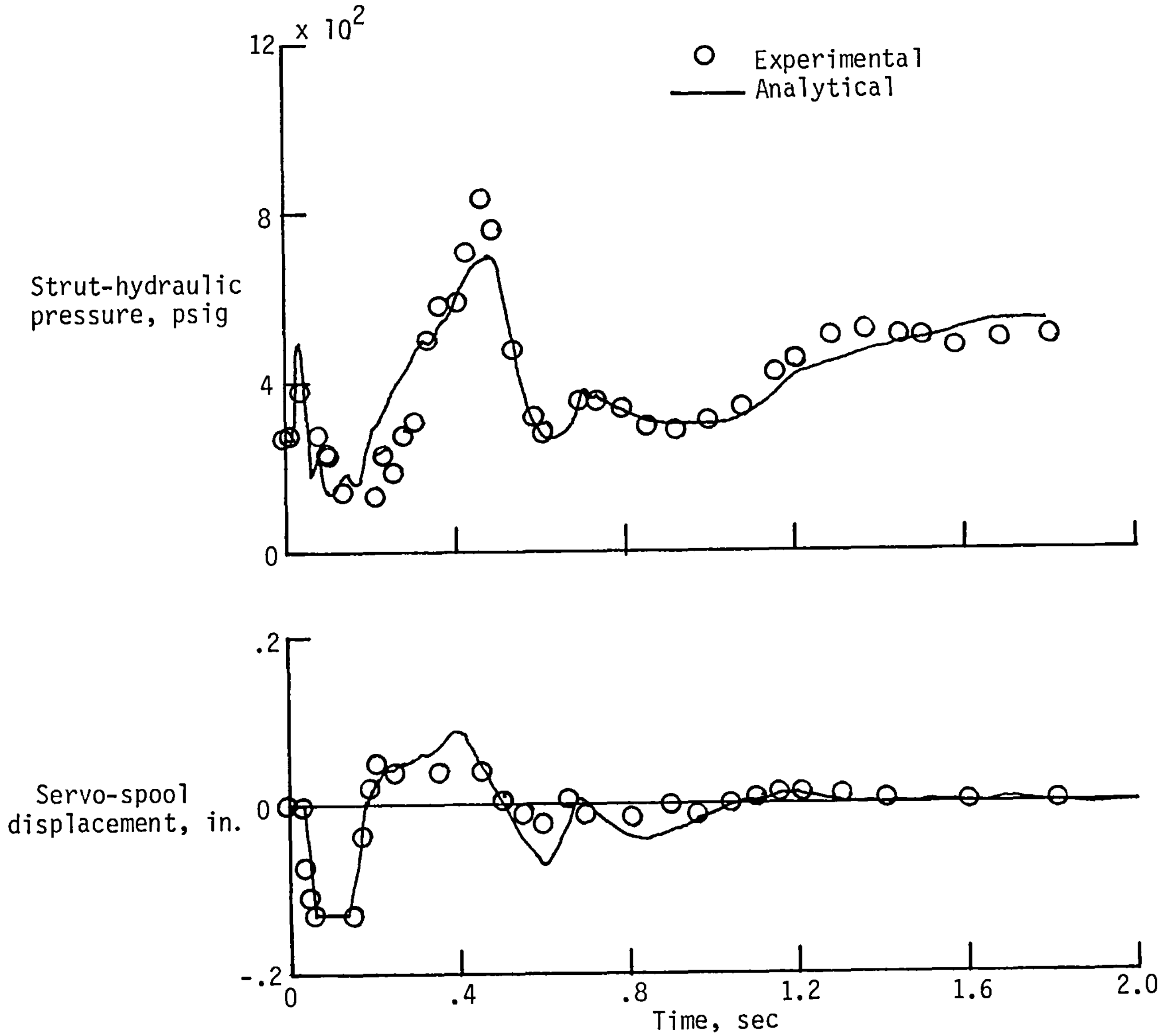
(b) Strut-hydraulic pressure for passive gear. Test 49 of reference 14.

Figure 6. Continued.



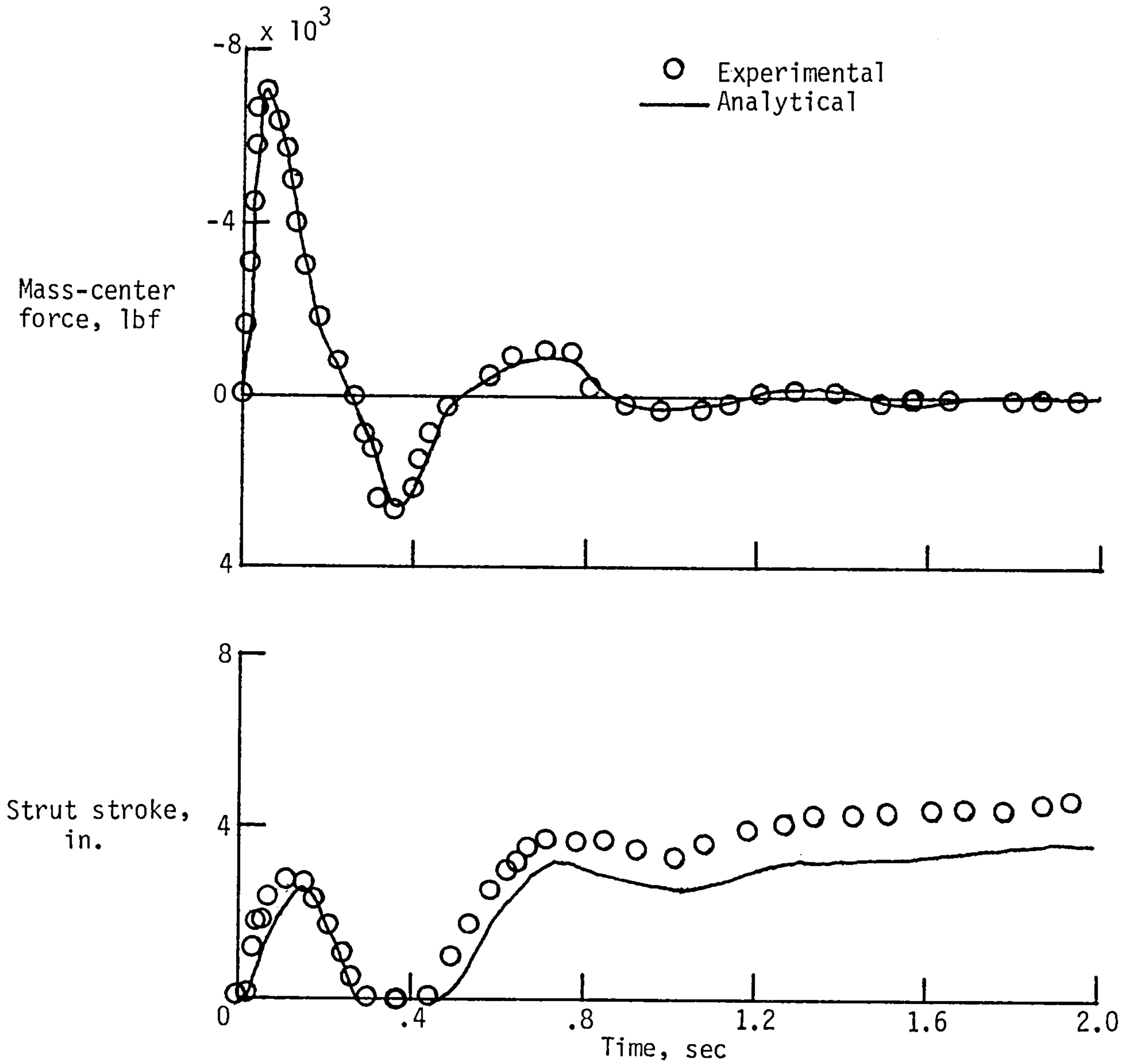
(c) Mass-center forces and shock-strut strokes for active gear. Test 51 of reference 14.

Figure 6. Continued.



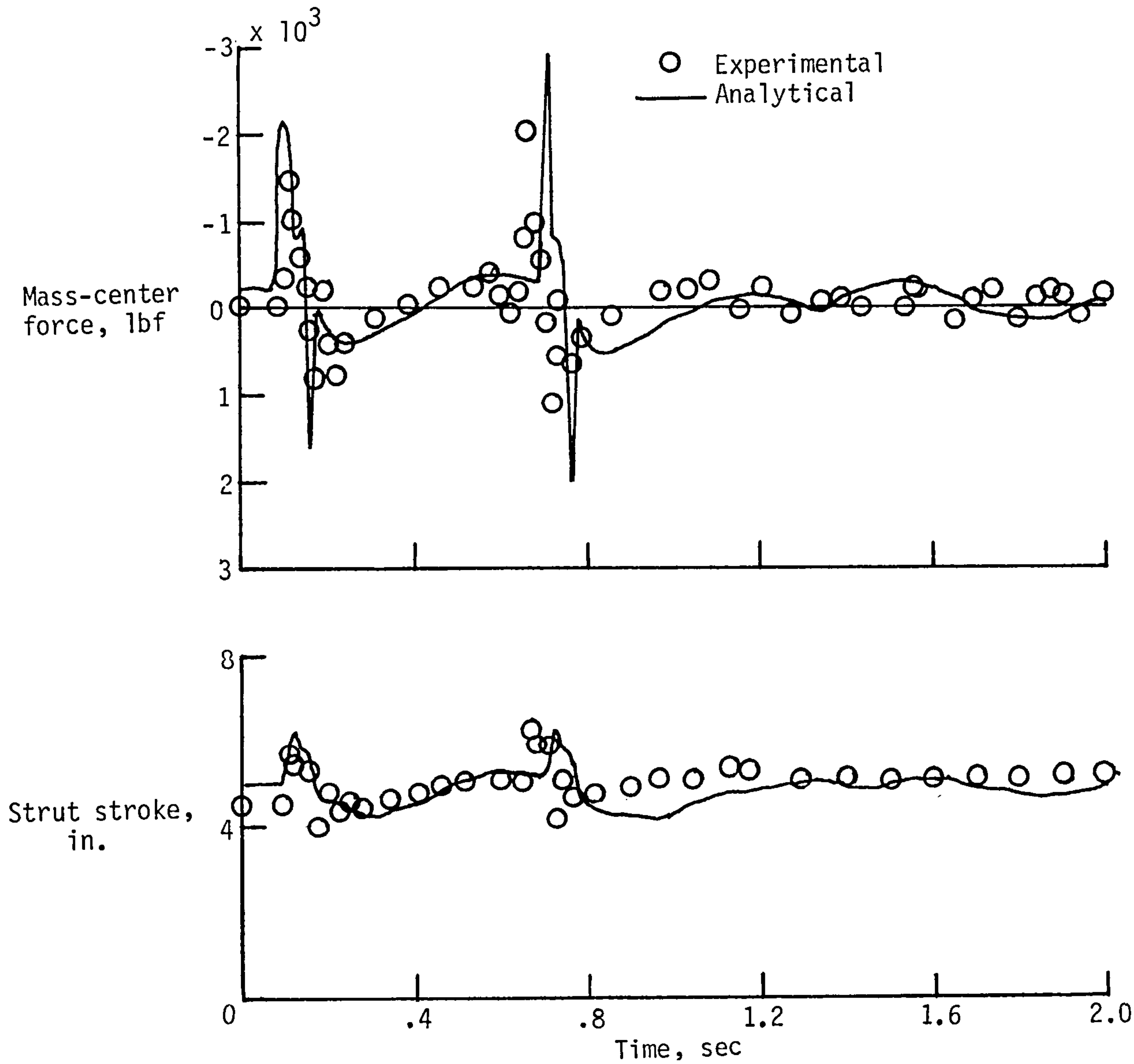
(d) Strut-hydraulic pressure and servo-spool displacement for active gear. Test 51 of reference 14.

Figure 6. Concluded.



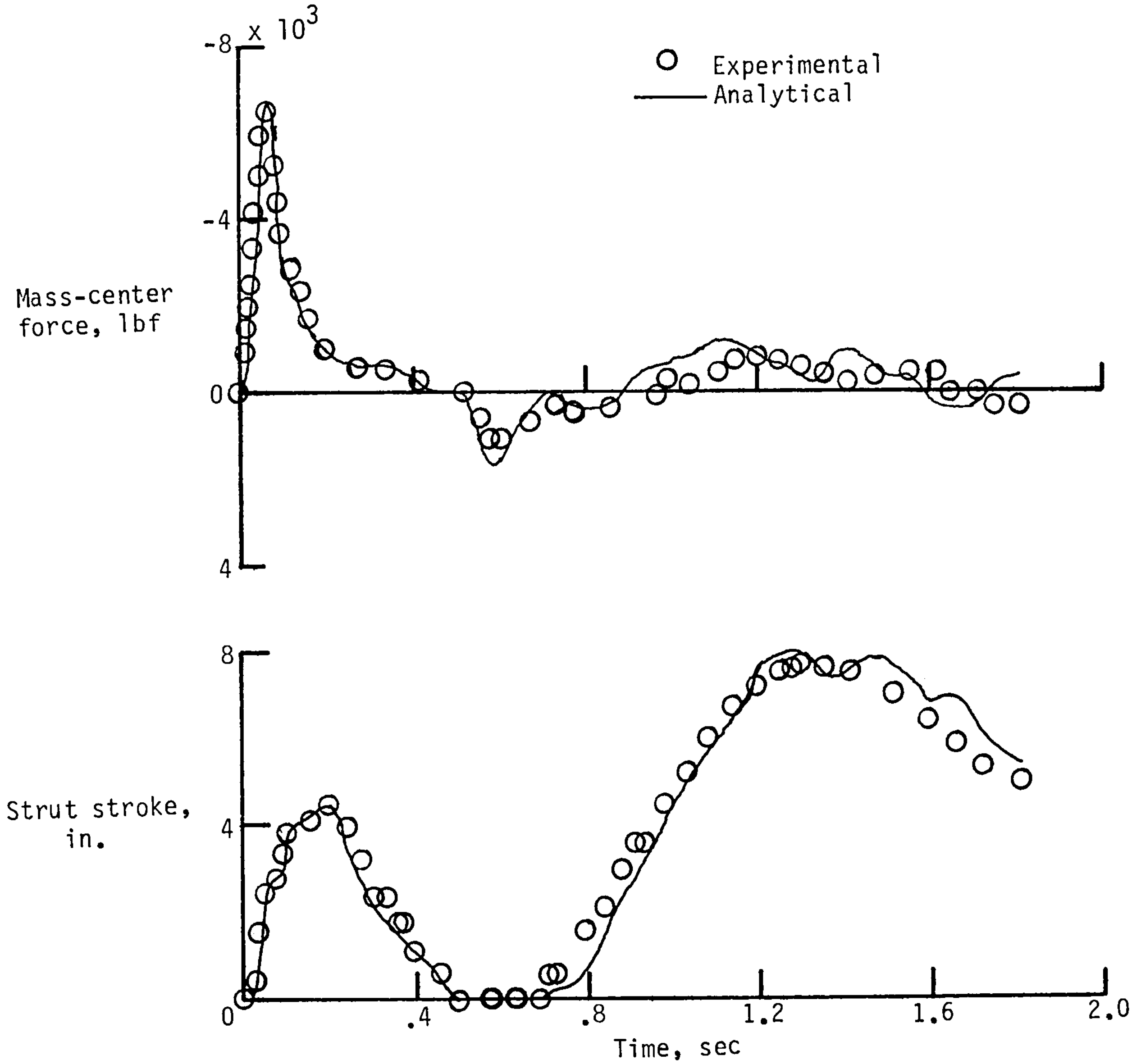
(a) Mass-center forces and shock-strut strokes for passive gear during touchdown impact. Test 40 of reference 15.

Figure 7. Experimental and analytical results from landing tests. Ground speed, 80 knots; touchdown sink rate, 5.5 fps; pitch attitude, 2°.



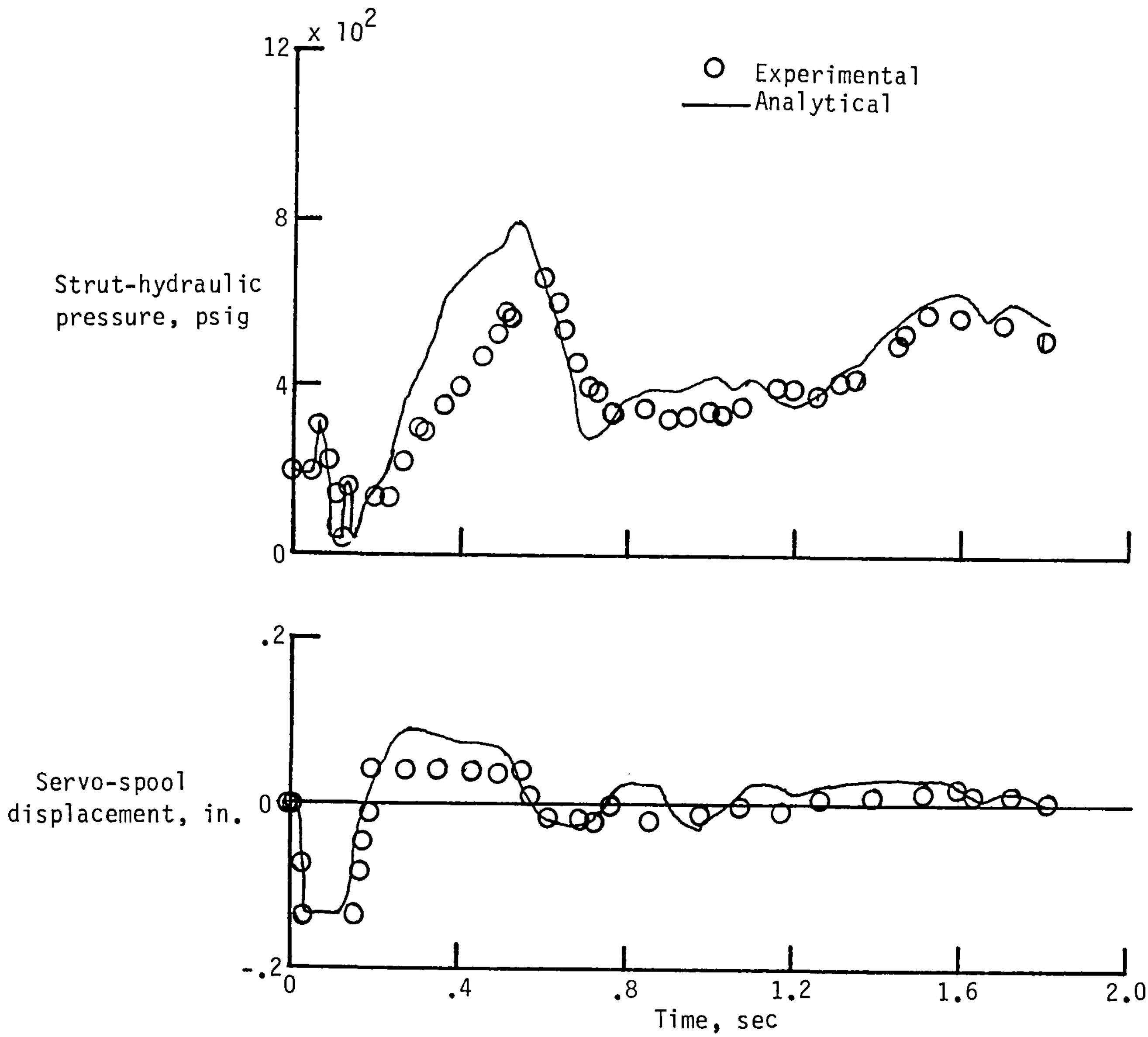
(b) Mass-center forces and shock-strut strokes for passive gear during traverse of step bumps. Test 40 of reference 15.

Figure 7. Continued.



(c) Mass-center forces and shock-strut strokes for active gear during touchdown impact. Test 42 of reference 15.

Figure 7. Continued.



(d) Strut-hydraulic pressure and servo-spool displacement for active gear during touchdown impact. Test 42 of reference 15.

Figure 7. Concluded.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TP-2353		

4. Title and Subtitle	5. Report Date
VALIDATION OF AN ACTIVE GEAR, FLEXIBLE AIRCRAFT TAKE-OFF AND LANDING ANALYSIS (AGFATL)	September 1984
	6. Performing Organization Code 505-45-14-01
7. Author(s) John R. McGehee	8. Performing Organization Report No. L-15807
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665	10. Work Unit No.
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	13. Type of Report and Period Covered Technical Paper
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The results of an analytical investigation using a computer program for active gear, flexible aircraft take-off and landing analysis (AGFATL) are compared with experimental data from shaker tests, drop tests, and simulated-landing tests to validate the AGFATL computer program. Comparison of experimental and analytical responses for both passive and active gears indicates good agreement for shaker tests and drop tests. For the simulated-landing tests, the passive and active gears were influenced by large strut-binding friction forces. The inclusion of these undefined forces in the analytical simulations was difficult, and consequently only fair to good agreement was obtained. An assessment of the results from the investigation indicates that the AGFATL computer program is a valid tool for the study and initial design of series-hydraulic active control landing-gear systems.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Aircraft landing gear Active controls Landing loads Landing analysis	Unclassified - Unlimited Subject Category 05

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	29	A03

National Aeronautics and
Space Administration

Washington, D.C.
20546

Official Business
Penalty for Private Use, $300

THIRD-CLASS BULK RATE

Postage and Fees Paid
National Aeronautics and
Space Administration
NASA-451

U.S.MAIL

NASA

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return