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AN EXPERIMENTAL SIMULATION STUDY OF FOUR CROSSWIND LANDING-GEAR CONCEPTS

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16. Abstract

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SUMMARY

An experimental investigation was conducted in order to evaluate several crosswind landing-gear concepts which have a potential application to tricycle-gear-configured, short take-off and landing (STOL) aircraft landing at crab or heading angles up to 30°. In this investigation, the landing gears were installed on a dynamic model which had a scaled mass distribution and gear spacing but no aerodynamic similarities when compared with a typical STOL aircraft. The model was operated as a free body with radio-control steering and was launched onto a runway sloped laterally in order to provide a simulated crosswind side force. During the landing rollout, the gear forces and the model trajectory were measured and the various concepts were compared with each other. Within the test limitations, the landing-gear system, in which the gears were alined by the pilot and locked in the direction of motion prior to touchdown, gave the smoothest runout behavior with the vehicle maintaining its crab angle throughout the landing runout.

INTRODUCTION

Airports constructed for short take-off and landing (STOL) aircraft will provide fewer choices for runway headings than conventional airports do, and thus will have the potential of exposing the aircraft to crosswinds which could impede landing and, possibly, take-off operations. In addition, STOL aircraft have typically low landing and take-off speeds which further contribute to their vulnerability to crosswinds. It is conceivable that under some conditions the velocity of the crosswind could be as high as 50 percent of the touchdown speed of such aircraft. There are several techniques employed by pilots to land an airplane equipped with conventional gear under the influence of a crosswind. The most preferred technique is to crab, or head the airplane into the wind during the approach, and to perform a transition maneuver (decrabbing or slipping the aircraft) immediately prior to touchdown. This transition maneuver and the subsequent rollout could pose problems to STOL aircraft where crab angles up to 30° are encountered. These problems include: excessive gear loading and passenger discomfort associated with an imperfect decrab maneuver; an increased workload required of the pilot in regulating the powered lift, monitoring airspeed, decrabbing the airplane, and so forth; and controlling the aircraft once on the ground to keep it within the confines of the runway. Some of these problems were emphasized in a recent simulator study conducted on a STOL transport; they are discussed in reference 1. In that study, the pilots concluded that during landing, a continuous wings-level crabbed touchdown and crabbed rollout was preferred to conventional techniques. However, to provide an airplane with a crabbed touchdown and rollout capability would necessitate an unconventional or crosswind landing-gear system.

Several landing-gear concepts, proposed in the late 1940's and early 1950's, would permit an aircraft touchdown in a crabbed attitude. These concepts, described in references 2 to 6, were originally developed for tail-wheel aircraft and some flight experience was obtained with various concepts on several aircraft. One of the concepts is currently employed on the B-52 and C-5A aircraft, but with a 20° crab-angle limitation. Comparative tests to establish whether this concept is the best approach for tricycle-geared STOL aircraft, operating at crab angles up to 30°, have not been conducted.

The purpose of this paper is to present the results of an experimental investigation conducted in order to evaluate various crosswind landing-gear concepts which have application to tricycle-gear-configured STOL aircraft landing at crab angles up to 30°. In this investigation, four different crosswind gear concepts utilizing a free-body, radio-controlled, dynamic model on a runway sloped laterally to simulate a crosswind side force were tested. Different steering techniques were used for the gear concepts. The model track and heading of the four concepts were compared with one another to show the behavioral characteristic of each gear concept during the landing runout. The basis for the evaluation of the various gear concepts was minimum vehicle lateral excursions and pilot effort.

APPARATUS AND PROCEDURE

The crosswind landing study was conducted in an enclosed facility using a simple radio-controlled dynamic model having a tricycle landing-gear arrangement. A side wind was simulated by using a laterally sloping runway; otherwise, no attempt was made to simulate aircraft aerodynamic effects on the model.

The study was conducted in two phases. The first phase employed a noninstrumented vehicle to obtain qualitative data for the various crosswind landing-gear concepts; preliminary results from that phase were discussed in reference 7. For the second phase, the vehicle was instrumented to obtain measurements of gear forces, gear steering angle, and wheel speed.

Description of Model

The model used in the investigation was patterned after a STOL-type aircraft. The model was not scaled aerodynamically; however, mass properties and gear spacing were simulated.

Basic vehicle.- A sketch of the model with the pertinent dimensions is given in figure 1 and photographs of both the noninstrumented and instrumented versions are presented in figure 2. Longitudinal and lateral aluminum angles were attached to a solid-model body in order to provide a means for mounting the ballast weights for obtaining the desired inertia properties. The pertinent mass parameters of the instrumented model are presented in table I. The tricycle landing-gear arrangement used on the model was composed of three identical gears. Detailed photographs of the landing-gear components are shown in figures 3 to 8 (and further discussion of the design is given in the appendix). Each gear was capable of being steered by radio-controlled servomechanisms, locked in any position, or free swiveling within the limits provided by mechanical stops. In addition, each gear possessed a simple drag brake which could be energized by a radio-control link. Two sizes of landing-gear forks were used to provide various amounts of trail or caster (offset distance of the tire behind the swivel axis). Bench tests were made to determine the best trail location for each landing-gear concept. Pneumatic, model airplane-type tires, 11.4 cm (4.5 in.) in diameter, were used on each gear.

Crosswind gear concepts.- Four crosswind landing-gear concepts were examined in this study. Figure 9 presents a schematic illustration of each concept together with a brief explanation of its operating technique both prior to and subsequent to touchdown.

Concept A utilizes free-swiveling gears prior to touchdown in order to achieve an alinement with the direction of the motion on contact. After alinement, the gears are either locked or steered. The steering can be accomplished by using only the nose gear, both the nose and the main gears together, or the nose and the main gears independently. A trail is needed on this configuration in order to aid in the rapid alinement of the gear when the tire contacts the runway.

In concept B all gears are free to swivel prior to touchdown, but mechanical stops, set on the main gear, prevent outward swiveling. The purpose of the stops is to facilitate the steering by developing side forces on the upwind main-gear wheel without actively having to lock the main gear at touchdown as for concept A. For concept B, the downwind wheel alines with the direction of motion but the upwind wheel is held against the stop until the vehicle decrabs to 0°. Should the vehicle decrab beyond 0°, a downwind side force is developed as the downwind wheel is then held against its stop. The steering is accomplished only through the nose gear.

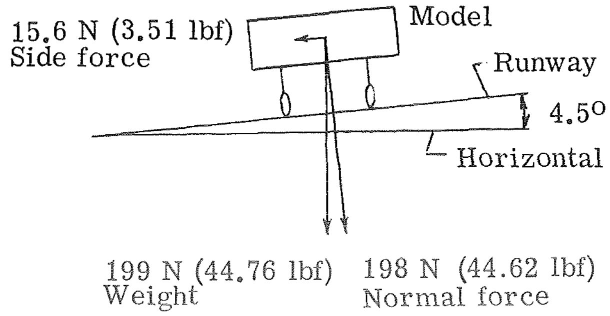
Concept C also allows all gears to swivel freely prior to touchdown, but differs from concepts A and B in that a crossbar linkage connects the forks on the main gear so they will act together. The geometry of the crossbar is such that a vehicle crab attitude induces a main wheel toe-out which varies proportionally with the crab angle. For this concept, toe-out is defined as occurring when the front of the main-gear tires are farther apart than the rear of the tires. It is theorized in concept C that the more heavily loaded downwind wheel will aline itself with the direction of motion and the more lightly loaded upwind wheel will toe-out, and thereby produce a small upwind side force to facilitate the steering. For the tests reported in this paper, the crossbar linkage was set to provide a 3° toe-out at a crab angle of 30°. Mechanical stops were added to this concept to restrict the main-gear swivel angle to $\pm 30^{\circ}$.

In concept D the pilot, prior to touchdown, presets all gears in the direction of motion. Since the gears require no self-alining mechanism at touchdown, no trail is needed for this concept. As with concept A, directional control during rollout can be accomplished by steering the nose gear only or by steering all gears.

Steering mechanism.- The model was steered remotely using radio-control equipment. Each gear was equipped with a single servomotor to engage a clutch which converted the landing gear from a free-swiveling to a steerable mode. Dual servomechanisms were used on each in order to provide the necessary steering torque. Each gear was steered by a separate transmitter-control stick and a mechanical linkage was inserted between the sticks when it was desirable to steer all gears together or to steer the nose and main gears independently. (Steering the nose gear only or steering all gears in the same direction concurrently required only one hand; steering independently required two hands, one for the nose gear and one for the main gears.) The radio-control system was proportional; that is, the servomechanisms displaced proportionally to the control-stick displacement.

Runway and Launch Apparatus

The runway and launch apparatus are shown in figure 10. The runway, 61 m (200 ft) long and 4.1 m (13.6 ft) wide, was covered with plywood in an attempt to achieve a smooth surface. The runway was inclined laterally 4.5° to simulate a crosswind side force on the model (see the following sketch) estimated to be equivalent to that which would occur in a 90° crosswind of one-half of the aircraft-landing velocity:



The launch apparatus as shown in figure 10 consisted of a model-supporting carriage mounted on a monorail. A continuous electrically powered, winch-driven cable was attached to the carriage and was used to accelerate the model and carriage to the desired horizontal velocity. Near the end of the monorail, the drive cable was separated from the carriage and the carriage was arrested, allowing the model to slip free and continue down the runway.

Instrumentation and Measured Parameters

Parameters measured during the course of each test consisted of the vehicle track and heading, both acquired from motion-picture coverage, and the touchdown velocity as determined from the speed of the launch carriage immediately prior to model release. The instrumented model was equipped to measure the time histories of the forces, the steering torque, the steering angle, and the wheel angular velocity of each gear, together with the vehicle normal acceleration.

Normal, longitudinal and lateral forces, and steering torque were measured on each landing gear using a six-component force balance specially developed for this model. The balance rotated with the gear assembly and thus the measured forces are oriented with the gear. To permit the resolution of the gear forces along the vehicle body axis, the steering angle of each gear with respect to the body was measured using a variable potentiometer geared to the shaft as shown in figure 4. A continuous wheel angular-velocity signal was derived from the frequency of pulses generated by an optical device which sensed each twelfth of a wheel revolution. (See fig. 8.) The normal acceleration of the vehicle was measured at the vehicle center of gravity by a piezoresistive, strain-gage accelerometer. Signals from these data-acquisition devices were multiplexed onboard the model and transmitted through four small coaxial cables to two frequency-modulated tape recorders. All the taped data except the wheel angular velocity were filtered in order to attenuate frequencies above 100 Hz. The wheel angular-velocity signal was attenuated above 1000 Hz and, in the data processing, all data were attenuated above 110 Hz and digitized at a sample rate of 500 samples/sec.

The force and torque loading applied to the balance and defined as positive are shown in figure 11. A positive steering angle is also shown. The data were corrected for balance interactions but not corrected for gear orientation. For instance, if the model is not level, normal force affects the longitudinal and lateral forces. The sign convention for the lateral and longitudinal model position and the heading angle are shown in figure 12 and an upward acceleration was considered positive.

Motion-picture coverage was obtained from six overhead cameras positioned along the runway in order to determine the vehicle runout trajectory and the model-to-runway heading angle. Two additional movie cameras recorded the entire runout and a video recorder was used to provide an immediate review of the test conditions and landing behavior. A time-code signal was recorded on the instrumentation tapes and along the edge of the movie film in order to facilitate data reduction from the tapes and to provide synchronization of the tape and the film data.

The model was positioned on the carriage close to the runway in order to minimize the vertical velocity at touchdown. The landing speed was determined electronically from the speed of the launch carriage during a coast phase which existed immediately prior to release of the model from the carriage.

Testing Technique

The testing technique involved launching the model as a free body in a crabbed attitude onto a laterally sloping runway. The behavior of the model to various steering inputs as it freely rolled to a stop was evaluated.

Before each run, the tire pressure, the trail position, and the initial model heading or crab angle were set and the gears were visually alined with the runway. After launch, the model became a free body steered to a complete stop through radio control by the operator at a position adjacent to the launch point. The brakes on the model were applied by the operator for only high-speed runs.

A number of runs were conducted using each of the landing-gear concepts with variations made in the initial crab angle, the landing speed, the initial gear alinement, the tire inflation pressure, and the steering technique. Most of the runs were made with the model preset on the carriage at a crab angle of 30°, which simulated an aircraft landing in a 90° crosswind equal to one-half of the landing speed. Similarly, most runs were initiated with model landing speeds of approximately 6.1 m/s (20 ft/s). These landing speeds simulated a full-scale velocity of 19 m/s (63 ft/s), and seemed to provide the most authentic simulation of the last two-thirds of a landing runout since aerodynamics would be less effective in this period. The lower speed also permitted better control and, hence, better differentiation between the various concepts that otherwise might not be controllable for this simulation at higher speeds. Another advantage of the lower speed was that braking, which could contribute complicating effects into the steering behavior, was not required. However, a few landings were made at model landing speeds of 11.4 m/s (37.4 ft/s) and brakes were applied.

RESULTS AND DISCUSSION

Limitations to Simulation

Early in the investigation several problems emerged that were inherent in relating the model results to those of a full-scale aircraft. One of the most apparent was related to the need for abnormally quick pilot response. For example, dimensional equivalence requires that the pilot's response for a 1/10-scale model be over three times that of a pilot of a full-scale aircraft. The response time lags of the radio-control system also aggravated this condition. These problems were compounded by the fact that the pilot was not in the vehicle where he could sense motion cues but, instead, was positioned near the touchdown point of the model where his visual cues diminished with model runout.

Another limitation in the simulation is that there was no thrust and aerodynamic control on the model to keep the horizontal forces in balance at touchdown and until steering of the landing gears could begin. For a STOL aircraft touching down in a crabbed attitude with a crosswind landing gear, it is assumed that the horizontal forces will be in equilibrium. The model, however, touching down on a laterally sloping runway, has an unbalance in forces that immediately starts a downwind drift which continues until the steering of the landing gears can be initiated. Because of the pilot response and the lags in the model radio-control mechanisms, when steering is finally attempted, the momentum of a downwind-drift velocity and any yaw angular velocity that has been initiated must be overcome. In order to minimize initial drift and yaw changes of the free swiveling concepts (concepts A, B, and C), some tests were made with the gears alined with the direction of motion and the steering engaged prior to touchdown, and thus the free-swiveling feature at touchdown was eliminated.

An additional limitation of the simulation was that the side force developed by the laterally sloping runway acts at the vehicle center of gravity instead of at the aerodynamic center of pressure. Therefore, there is no weathervaning moment such as might occur on an actual aircraft. This runway slope was maintained constant over the entire length of the runway and thus produced a constant side force perpendicular to the runway center line. In an actual aircraft landing, however, the side force, resulting from aerodynamics, varies during rollout because of changes in the windspeed and changes in the aircraft ground speed and heading with respect to the resultant airstream direction.

Although these problems with model testing place limitations on the direct application of the model test results to full-scale aircraft, these shortcomings apply to all four concepts investigated and a comparison of the relative merits of the various configurations appears to be justifiable.

Test Criterion

The basic criterion used in comparing the various landing-gear configurations was that the vehicle experience a minimum lateral displacement during rollout on the runway. Another requirement was that the vehicle have a minimum, or at least a slow yaw attitude change during runout; that is, a vehicle touching down at a 30° crab angle would run out at a 30° crab angle or would decrab slowly.

Noninstrumented Model Tests

Results in this section, obtained from over 60 runs, are qualitative in nature. They are presented in terms of the experience with the various gear concepts.

Concept A.- In the initial tests with concept A, the landing gears were free to swivel and, upon ground contact, to aline themselves with the direction of motion. In order to obtain alinement, some amount of trail was needed but it was found that there was a range of trail values that produced shimmy problems at a given tire-inflation pressure. After several tests, a trail of 1.3 times the tire radius and a tire-inflation pressure of 60 kPa (9 psi) were selected in order to eliminate the shimmy and to provide an adequate alinement capability. On the lighter loaded nose gear, a trail equal to one tire radius and an inflation pressure of 55 kPa (8 psi) were found to minimize the shimmy. In both cases, lower inflation pressures with or without shorter trail resulted in a moderate to a severe shimmy. Unfortunately, the need for long trail to reduce the shimmy imposed severe demands upon the available steering torque. Initial tests with concept A, and other concepts that were free to swivel prior to landing, gave poor landing behavior. When landings were made with all the gears prealined with the direction of motion and the steering clutch engaged prior to touchdown, very good crabbed runouts were obtained by utilizing only the nose-gear steering. When the steering is engaged prior to touchdown, concept A is similar to concept D except for the trail and the flexibility of the steering mechanism. The engagement of the steering clutch eliminates the free-swiveling feature at touchdown. Figure 13(a) shows sequence photographs of a typical run using concept A and only nose-gear steering. The runout was good, the vehicle maintaining a track very near the runway center line.

Figure 13(b) is a sequence of photographs showing a landing with steering control attempted by both nose and main gears turning equally and simultaneously, using one-steering input (one-hand control). When such steering was attempted, the results were not satisfactory because of either a slight preset misalinement of the gears with respect to each other, or a misalinement of the gears caused by uneven loading. The slight misalinement produced a slow continuing yaw change in the vehicle and, although the vehicle could be displaced laterally on the runway with steering, it would continue yawing until its gears hit mechanical stops, whereupon the vehicle diverged from the runway.

Steering the nose and main gears independently with two controls was also unsatisfactory even though some good runs were obtained. Figure 13(c) shows sequence photographs utilizing this independent steering. When differential inputs were made, such as steering nose gear windward and main gear leeward, the yawing motions were very rapid and confusing to the pilot, with an occasional loss of control as illustrated in the photographs. No attempt was made to steer the nose and main gears in opposite directions with a single steering input by the pilot. With reduced sensitivity and additional refinements, steering the nose and main gears independently might prove feasible; however, it was considered an unnecessary complication.

Concept B.- The main-landing gear of concept B was free to swivel only inward to aline with the direction of motion on ground contact. To facilitate the gear alinement, trail again was used – the same amount of trail as for concept A. When the vehicle landed crabbed or yawed into the wind, the nose gear and downwind main gear alined with the direction of motion. However, the upwind main gear was forced against a stop which kept it alined with the longitudinal axis of the model and produced a side force aft of the center of gravity into the wind. Only nosewheel steering was used with concept B, and for the test shown by the sequence photographs in figure 14(a) it was actuated after touchdown. For the sequence shown, a large windward side force was developed by the upwind tire alined at a 30° yaw angle with respect to the direction of motion. The large side force acting behind the vehicle center of gravity produced a large decrabbing or counterclockwise torque and a violent decrabbing motion. The angular momentum generated by the rapid decrabbing rendered the model uncontrollable. It was felt that the violent decrabbing motion caused by the upwind wheel could be reduced, but not altogether eliminated, on an actual aircraft by directional stability and rudder control.

Additional runs were made with concept B, wherein the nose gear and downwind main gear were prealined with the direction of motion and the nose steering clutch was engaged prior to touchdown. Photographic results of this test are presented in figure 14(b). The model decrabbed rapidly as shown between the first and second photographs and full right-steering input (30°) was needed throughout the remaining runout in order to maintain control. This type of steering imput was marginal and was considered to be unsatisfactory.

Concept C.- As with concepts A and B, the landing gear of concept C was free to swivel prior to contact and, like that of concept B, only nosewheel steering was available. The trail used to achieve alinement was the same as that for concepts A and B. Since both main gears were tied together by a crossbar linkage, it would be expected that the downwind gear, which was more heavily loaded, would aline itself with the direction of motion. The more lightly loaded upwind gear would toe-out (3° for 30° crab angles) and produce a small force in the windward direction to facilitate steering.

No satisfactory runs were made when the steering clutch was engaged after contact. When the gear was alined with the direction of motion and the steering clutch engaged prior to contact, good runs were obtained at a 30° crab angle. (See fig. 15(a).) However, it was necessary in those tests to set mechanical stops on the main gear at 30°; otherwise, during runout the tail would continue to swing downwind. To support these findings several landings were made at 0° yaw (fig. 15(b)). An undesirable yaw motion was observed for all landings until the main gear hit the 30° stops, as is shown to occur during the run in frame 4 and again in frame 12 of figure 15(b). Throughout this crabbing maneuver, it was found that the nose gear must be steered or the model would be uncontrollable. The toe-out of this concept did not produce enough side force to facilitate steering and there was no directional control unless the main gear was against a mechanical stop.

Concept D.- For a landing using concept D, it is assumed that a mechanism would be provided to permit the pilot to aline all three landing gears with the direction of motion and to lock them in position prior to touchdown. Since the self-alining feature was not needed, no trail was used for this concept. With no trail on the landing gears, there was no shimmy problem, the torques required to steer the model were considerably reduced, and the steering was quite responsive. Thus, in effect, concept D is essentially the same as concept A when the gear of A is alined and locked in the direction of motion; however, concept D lacks the shimmy tendency and the severe steering-torque demands that occur for the long trail required for concept A. Good runs were obtained immediately by using concept D with nose-gear steering. Figure 16 shows a typical run where the model touched down in a 30° crab and a straight, uneventful runout followed.

An interesting observation with this concept was that, even though the model was crabbed 30° and the gear lined up with the direction of motion, the model weathervaned or crabbed even farther because of the uneven loading of the main gears. With no steering inputs, the vehicle on touchdown moved leeward slightly, then weathervaned, and started a slow windward drift. Small leeward steering inputs are needed for control, and control is relatively easy. Several runs were made with a 5° preset error in the gear alinement with the direction of motion in order to simulate pilot error. The vehicle was controllable but not without some initial weaving down the runway. When 10° errors in alinement were tried, the vehicle was still controllable but initial lateral motions tended to be excessive and some tire squeal was noted. With aerodynamic controls, however, it was felt that landings with even larger alinement errors could be satisfactorily made.

As was observed with concept A, steering all gears of concept D together was unsatisfactory because a slow ground loop resulted. Steering both nose gear and main gears independently was tried and a satisfactory run was obtained. However, independent steering increased the sensitivity of an already adequately sensitive steering system and added an unnecessary complication.

Instrumented Model Tests

Eight representative cases were chosen from over 70 instrumented tests for quantitative discussion. The cases are summarized in table II and detailed time histories of these cases have been included in figures 17 to 24. All tests were made with the initial crab angle preset to 30°, the gears alined with the runway, and the steering clutch engaged (not free swiveling) prior to touchdown. For all but the last case of table II, the lower landing speed, which simulated the last two-thirds of a landing rollout, was used and no braking was applied. These cases include effects due to two tire pressures and two steering techniques. For gear concepts A, B, and C, the wheels were positioned in their forks to have 0.052 m (2.04 in.) trail on the nose gear and 0.071 m (2.79 in.) trail on the main gears; smaller forks without trail were used in concept D. To aid in interpreting the results from the instrumented tests, the following paragraphs discuss in detail (1) a typical time history and (2) the maximum value model data for the cases presented.

Time histories.- The time histories derived from case 1 and presented in figure 17 have been arbitrarily selected for discussion. These histories describe the rollout characteristics of concept A utilizing only nose-gear steering. Force data are presented in figure 17(a) and acceleration, steering angle (gear position), wheel angular velocity, vehicle displacements, and heading data are presented in figure 17(b). The run starting time for the time-history data was determined by the first indication of force on one of the three landing gears. Dashed-line fairings of the maximum-force data (fig. 17(a)) are an attempt to eliminate structural oscillations caused by model and gear elasticity. The maximum values obtained from such fairings are presented in table II. Because the steering inputs are small in this run, the longitudinal and lateral forces during the runout were relatively constant.

The normal acceleration shown in figure 17(b) has oscillations at approximately the same frequency as the normal-force traces of the main gears shown in figure 17(a). The oscillations in the steering angle at the start indicate a brief shimmy of the nose gear before the steering becomes steady. The right and left main-gear steering angles remained constant throughout the run because they were locked. Except for initial transients in the wheel angular-velocity traces, a smooth velocity decay is shown for each wheel. The good controllability of this run is reflected in the smoothness of the lateral displacement and the heading-angles traces. The greatest lateral displacement from the runway center line was approximately 0.5 m (20 in.) and heading angle changes were small and gradual indicating a smooth runout.

Maximum value data.- A summary of the maximum values obtained from the eight time-history records (figs. 17 to 24) is given in tabular form in table II. Figure 25 is a bar chart of runout distance and excursions in the vehicle lateral displacement and the heading angle for the four concepts. Windward lateral and yawing excursions were considered to be positive. In general, concepts A and D have smoother runouts than do concepts B and C. In the trajectory of concept B the vehicle decrabbed to 0°, which required the steering-control stick to be held hard over against a stop in order to maintain control.

CONCLUDING REMARKS

An experimental investigation was conducted to evaluate various crosswind landing-gear concepts which have potential application to tricycle-gear-configured, short take-off and landing (STOL) aircraft landing at crab angles up to 30°. Four crosswind gear concepts were tested by utilizing a free-body, radio-controlled model having a scaled mass distribution and gear spacing but no aerodynamic similarities. The model was landed on a runway sloped laterally to simulate a crosswind side force.

Relative comparisons of the concepts were made but certain limitations were found that were inherent in relating the model results to those of a full-scale aircraft. The more significant of these were the lack of motion cues to the pilot, the requirement that the pilot respond three times as fast as is necessary for the full-scale aircraft, and the lack of aerodynamic control at touchdown.

Of the concepts examined, concept D, which required the pilot to aline all three gears in the direction of motion prior to touchdown and to steer with the nose gear about the pre-set landing-gear position, gave the best performance. Satisfactory runs were consistently made with this system even when the gears were misalined up to 10° at touchdown.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., January 20, 1975.

APPENDIX

CROSSWIND LANDING-GEAR DESIGN

Each of the three landing gears of the short take-off and landing crosswind model was identical in design and construction. A photograph of a gear is presented in figure 3 where the principal subassemblies are identified. The upper section constitutes the steering-control system, the middle section defines that portion of the gear which is attached to the body of the model, and the lower section comprises the force balance and the tire, wheel, and brake assembly. A closeup photograph of the upper and midsections with callouts of the visible components is presented in figure 4 and all component parts for these sections are pictured in figures 5 and 6. The lower section is shown in figure 7, and its components in figure 8. The three sections are connected by a steering shaft, shown in figure 6, which transmits any applied steering torque to the tire. To convert the gear from a free swiveling to a steerable mode, the steering-actuator servomechanism identified in figure 4 was used to engage a spring-loaded clutch. Also shown in figure 4 is the gear position potentiometer for landing-gear yaw-position measurements. For those runs using the restrained mode for the main gear, a mechanical-stop plate and pin (fig. 4) were used to fix the gear.

The force balance (figs. 7 and 8) was a lightweight, six-component balance but, because of the other instrumentation limitations, only four components were recorded. The wheel fork (fig. 8) was fabricated to provide three possible trail positions and a simple spring-loaded friction brake was used to provide a fixed brake force for the high-speed runs. The angular velocity pickup, also shown in figure 8, was mounted on the wheel fork in order to monitor wheel angular velocity.

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5. Anderson, Seth B.; Gadeberg, Burnett L.; and McAvoy, William H.: Effect of a 90° Cross-Wind on the Take-Off Distance of a Light Airplane Equipped With a Cross-Wind Landing Gear. NACA TN 1898, 1949.

6. Breuhaus, W. O.; and James, C. W.: Taxi, Take-Off, and Landing Tests of an Ercoupe Airplane Equipped With a Cross-Wind Landing Gear. Rep. No. BC-717-F-1, Cornell Aeronaut. Lab., Inc., Aug. 28, 1951.

7. Stubbs, Sandy M.; and Byrdsong, Thomas A.: Model Studies of Crosswind Landing-Gear Configurations for STOL Aircraft. 8th Aerospace Mechanisms Symposium, NASA TM X-2934, 1973, pp. 145-154.

TABLE I.- MASS PARAMETERS OF INSTRUMENTED CROSSWIND MODEL

Complete vehicle (nominal)	SI Units	U.S. Customary Units
Mass	20.3 kg	1.39 slugs
Roll mass moment of inertia	1.88 kg-m^2	1.39 slug-ft^2
Pitch mass moment of inertia	2.05 kg-m^2	1.51 slug-ft^2
Yaw mass moment of inertia	3.58 kg-m^2	2.64 slug-ft^2
Components:		
Gear mass, long fork	0.724 kg	0.04961 slug
Gear mass, short fork	0.655 kg	0.04488 slug
Tire mass	0.221 kg	0.01513 slug

TABLE II. - SUMMARY OF TEST CONDITIONS AND RESULTS

Case	Crosswind gear concept	Steering technique	Touchdown velocity, m/s (ft/s)	Initial crab angle, deg	Tire pressure			Landing-gear trail			Runout distance, m (ft)	Lateral excursion range, m (in.) -Left, +Right	Aircraft/runway heading angle range, deg
					Nose, kPa (lbf/in^2)	Right main, kPa (lbf/in^2)	Left main, kPa (lbf/in^2)	Nose, m (in.)	Right main, m (in.)	Left main, m (in.)			
1	A	Nose gear	6.31 (20.7)	30	69 (10)	62 (9)	62 (9)	0.052 (2.04)	0.071 (2.79)	0.071 (2.79)	40 (131)	0.5, -0.08 (20, -3)	21 to 34
2	A	(*)	6.40 (21)	30	69 (10)	69 (10)	69 (10)	0.052 (2.04)	0.071 (2.79)	0.071 (2.79)	45 (148)	0.4, -1.0 (16, -39)	24 to 75
3	B	Nose gear	6.22 (20.4)	30	69 (10)	62 (9)	62 (9)	0.052 (2.04)	0.071 (2.79)	0.071 (2.79)	33 (108)	0.45, -0.38 (18, -15)	27 to -4
4	C	Nose gear	6.16 (20.2)	30	69 (10)	62 (9)	62 (9)	0.052 (2.04)	0.071 (2.79)	0.071 (2.79)	36 (118)	-0.72, 0.08 (-28, 3)	18 to 33
5	D	Nose gear	6.81 (22.34)	30	62 (9)	62 (9)	62 (9)	0 (0)	0 (0)	0 (0)	45 (148)	-0.3, 0.27 (-12, 11)	40 to 24
6	D	Nose gear	6.55 (21.5)	30	62 (9)	62 (9)	62 (9)	0 (0)	0 (0)	0 (0)	38 (125)	0, -0.7 (0, -28)	22 to 49
7	D	Nose gear	7.32 (24.0)	30	62 (9)	62 (9)	62 (9)	0 (0)	0 (0)	0 (0)	34 (112)	0.44, -0.81 (17, -32)	8 to 40
8	D	Nose gear	11.4 (37.4)	30	69 (10)	62 (9)	62 (9)	0 (0)	0 (0)	0 (0)	40 (131)	-0.9, 0.42 (-35, 17)	20 to 47

*Steering both nose and main gears independently.

TABLE II.- SUMMARY OF TEST CONDITIONS AND RESULTS – Continued

Case	Crosswind gear concept	Maximum nose gear forces				Maximum right main gear forces				Maximum left main gear forces			
		Normal, N (lbf)	Longitudinal, N (lbf)	Lateral, N (lbf)	Steering torque, N-m (in/lbf)	Normal, N (lbf)	Longitudinal, N (lbf)	Lateral, N (lbf)	Steering torque, N-m (in/lbf)	Normal, N (lbf)	Longitudinal, N (lbf)	Lateral, N (lbf)	Steering torque, N-m (in/lbf)
1	A	-62 (-14)	0 (0)	12 (2.8)	-0.84 (-7.4)	-50 (-11)	-1.3 (-0.3)	15 (3.3)	-0.90 (-8.0)	-116 (-26.1)	-8.4 (-1.9)	-8.0, 5.8 (-1.8, 1.3)	-1.68 (-14.9)
2	A	-49 (-11)	-4.4 (-1.0)	11 (2.4)	-0.70 (-6.2)	-54 (-12)	-5.3 (-1.2)	20 (4.5)	-1.1, 0.10 (-9.7, 0.89)	-144 (-32.4)	-14.0 (-3.1)	23, -4 (5.1, -0.9)	>-2.26 (>-20.0)
3	B	-49 (-11)	-8.8 (-2.0)	7.1 (1.6)	-0.46 (-4.1)	-75.62 (-17)	-4.8 (-1.1)	>44 (>9.9)	>±2.24 (>±19.8)	-117 (-26.3)	-9.3 (-2.1)	-2.0 (-0.4)	-0.14, 0.28 (-1.2, 2.5)
4	C	-53 (-12)	6.2 (1.4)	13 (2.9)	-0.78 (-6.9)	-50 (-11)	8.8 (2.0)	40 (9.0)	-1.32 (-11.7)	-115 (-25.9)	-16.4 (-3.7)	40, 2.4 (9.0, -0.5)	-0.62 (-5.5)
5	D	-22 (-4.9)	3.6 (0.8)	8.0 (1.8)	-0.04 (-0.35)	-75 (-17)	-0.8 (-0.2)	20 (4.5)	-0.26 (-2.3)	-100 (-22.5)	-6.0 (-1.3)	9.8 (2.2)	-0.50 (-4.4)
6	D	-32 (-7.2)	-2.2 (-0.5)	9.3 (2.1)	-0.06 (-0.53)	-75 (-17)	-1.8 (-0.4)	-38, 24 (-8.5, 5.5)	1.24, -0.28 (-11.0, -2.5)	-123 (-27.7)	-4.0, 5.3 (-0.9, 1.2)	-39, 17 (-8.7, 3.9)	0.48, -0.96 (4.2, -8.5)
7	D	-31 (-7.0)	3.1 (0.7)	17, -14 (-3.9, -3.2)	0.06, -0.08 (-0.53, -0.71)	-115 (-25.9)	0 (0)	32, -30 (7.3, -6.7)	0.58, -0.30 (5.1, -2.7)	-134 (-30.1)	-16.8 (-3.8)	31, -24 (6.9, -5.5)	-1.14 (-10.1)
8	D	-44 (-10)	-4.4, -12.4 (-1.0, -2.8)	-9.3, 12 (-2.1, 2.7)	-0.08, 0.28 (-0.71, 2.5)	-110 (-24.7)	-6.2 (-1.4)	30, -10 (6.7, -2.2)	-0.10, 0.10 (-0.89, 0.89)	-120 (-27.0)	-16.4 (-3.7)	8.0, -15 (1.8, -3.4)	0.20, -1.0 (1.8, -8.9)

TABLE II.- SUMMARY OF TEST CONDITIONS AND RESULTS – Concluded

Case	Crosswind gear concept	Remarks	Notes
1	A	Good runout.	Simulated a free-swiveling gear prior to touchdown.
2	A	Large lateral displacements and heading changes.	Steering both nose and main gear independently.
3	B	Abrupt motions at touchdown, runout barely controllable.	Main gears swivel limited by stops.
4	C	Good runout.	Crossbar linkage between main gears.
5	D	Good runout.	All gears alined with direction of motion.
6	D	Abrupt motions at touchdown, but controllable.	All gears misalined leeward 10°.
7	D	Abrupt motions at touchdown, but controllable.	All gears misalined windward 10°.
8	D	Model pilot response inadequate for initial speed, but runout was satisfactory.	High velocity run with brakes.

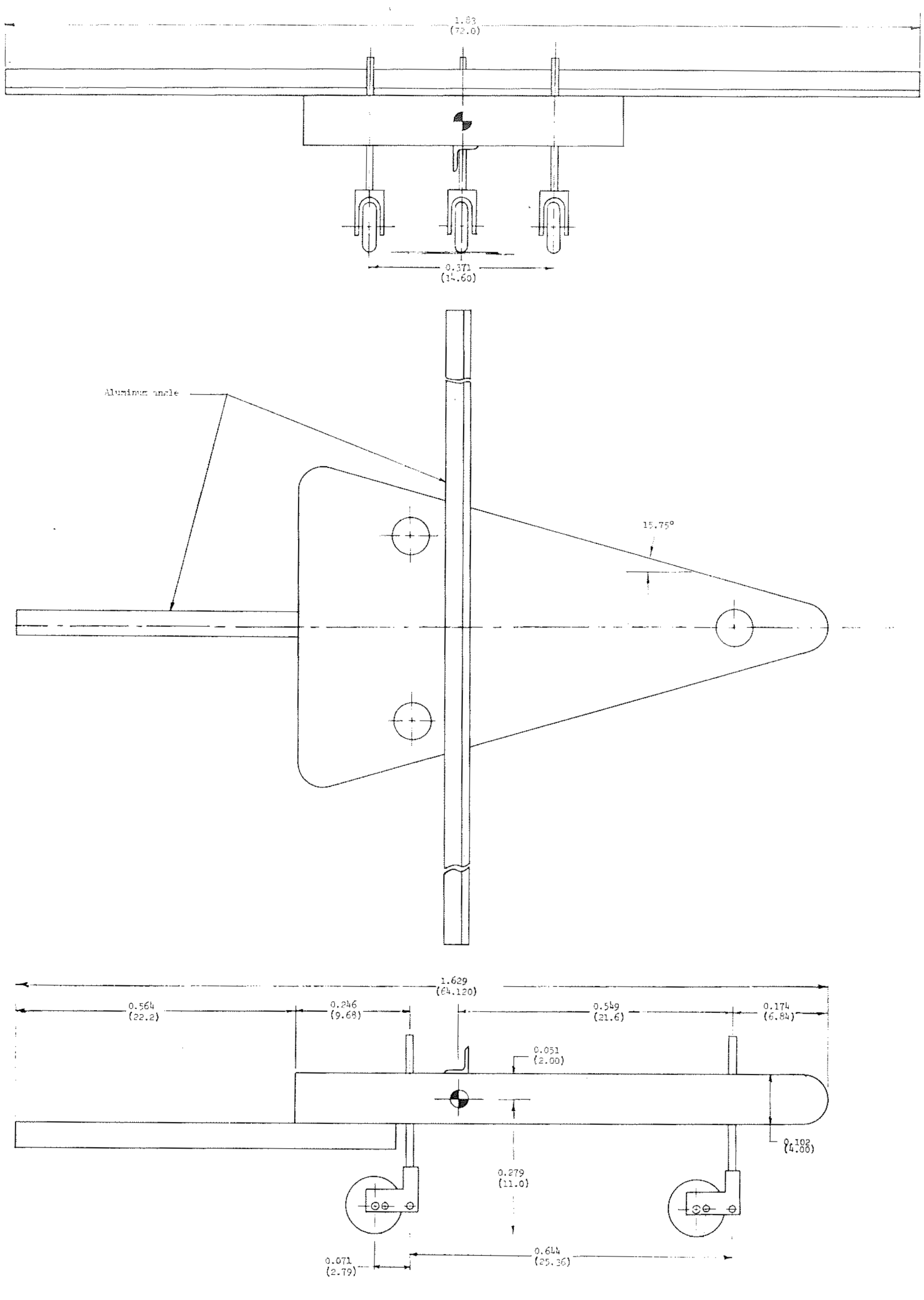
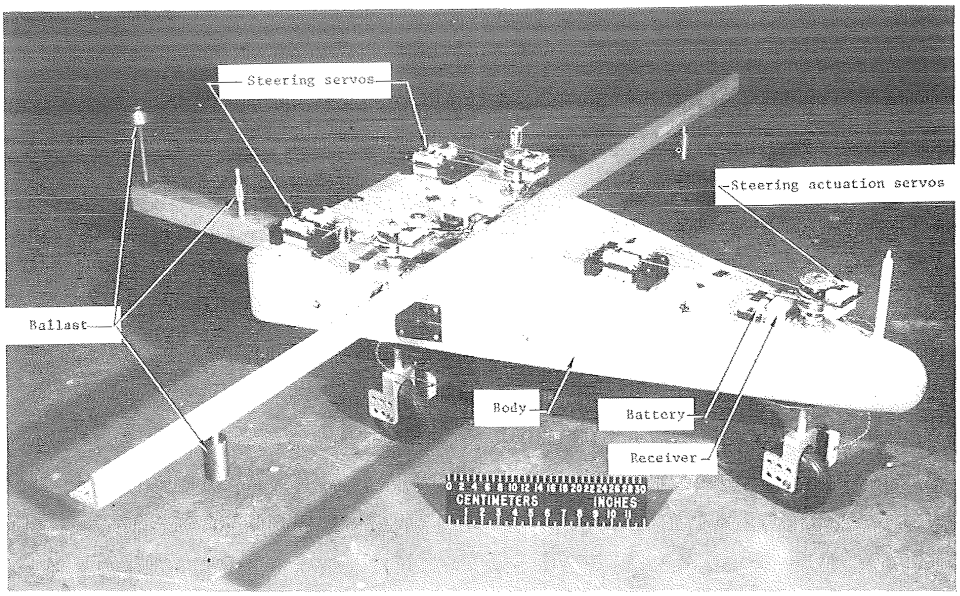
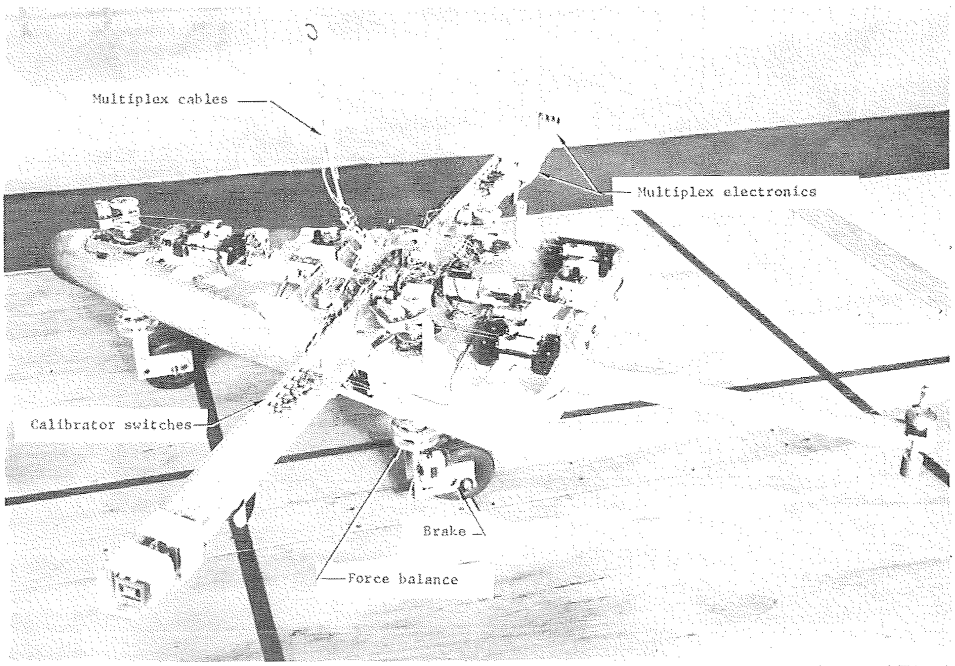


Figure 1.- Crosswind model configuration. Dimensions are given in meters and parenthetically in inches.



L-72-4848.1

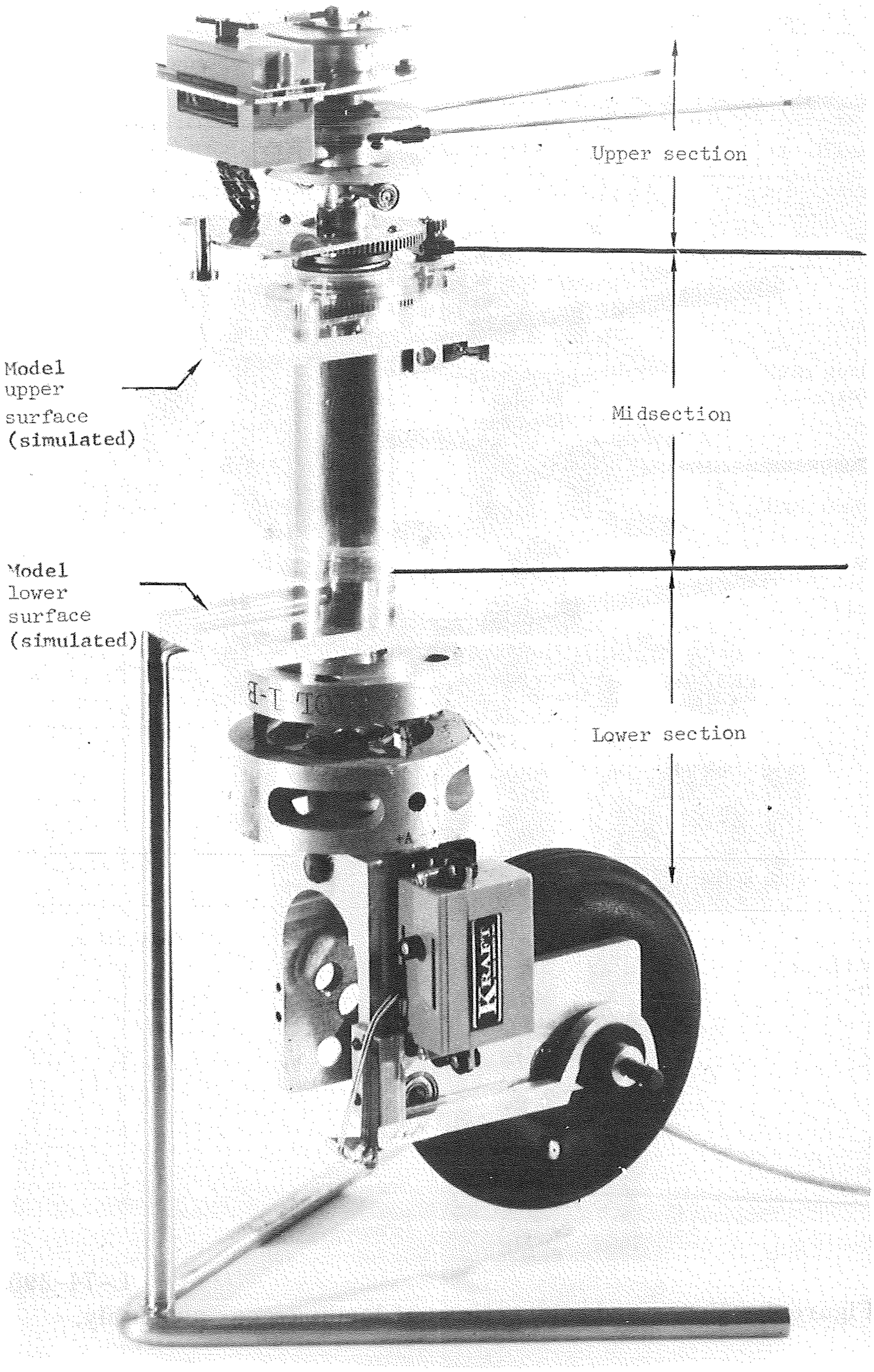
(a) Noninstrumented model.



L-73-5475.1

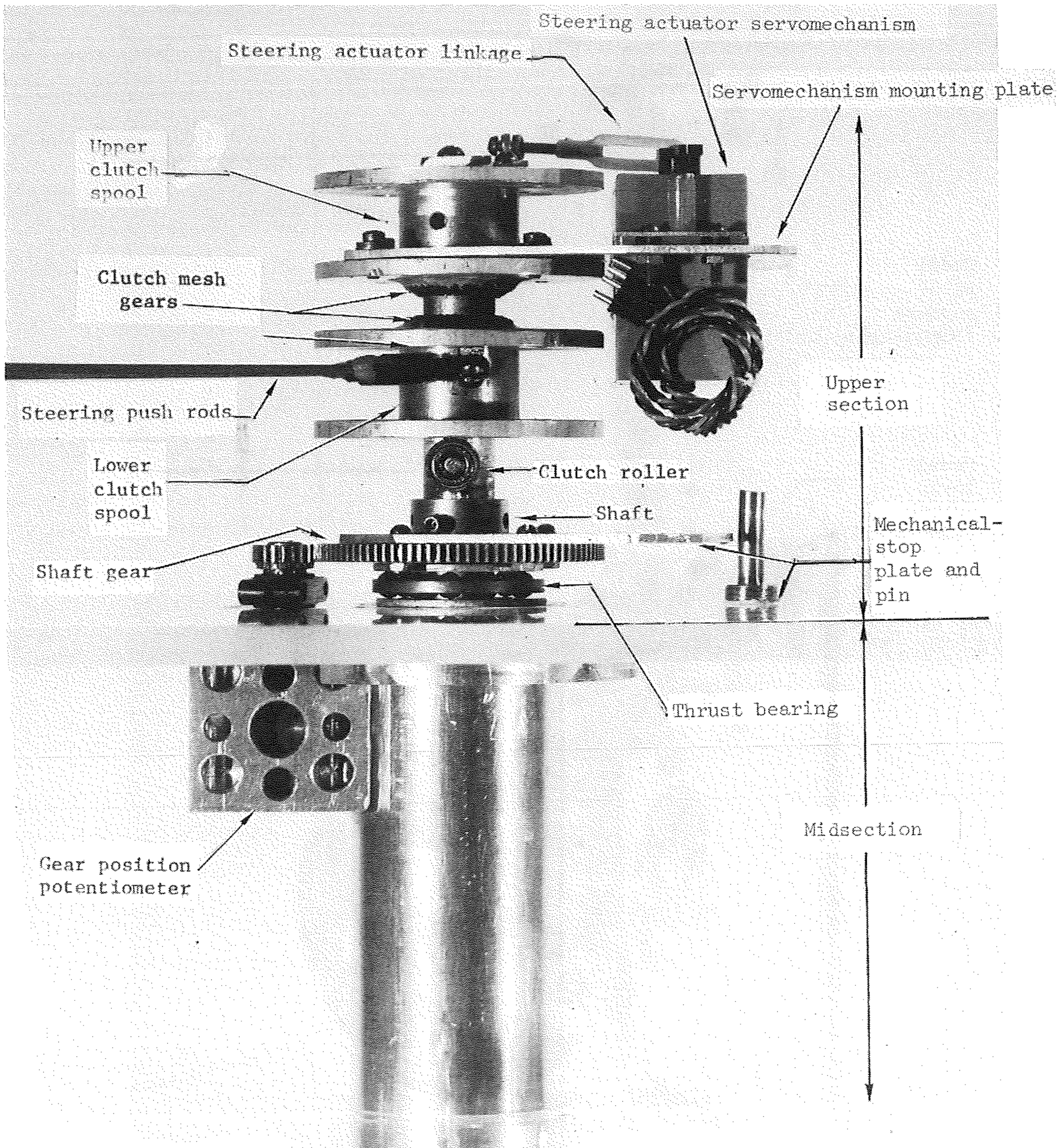
(b) Instrumented model.

Figure 2.- Crosswind landing-gear test models.



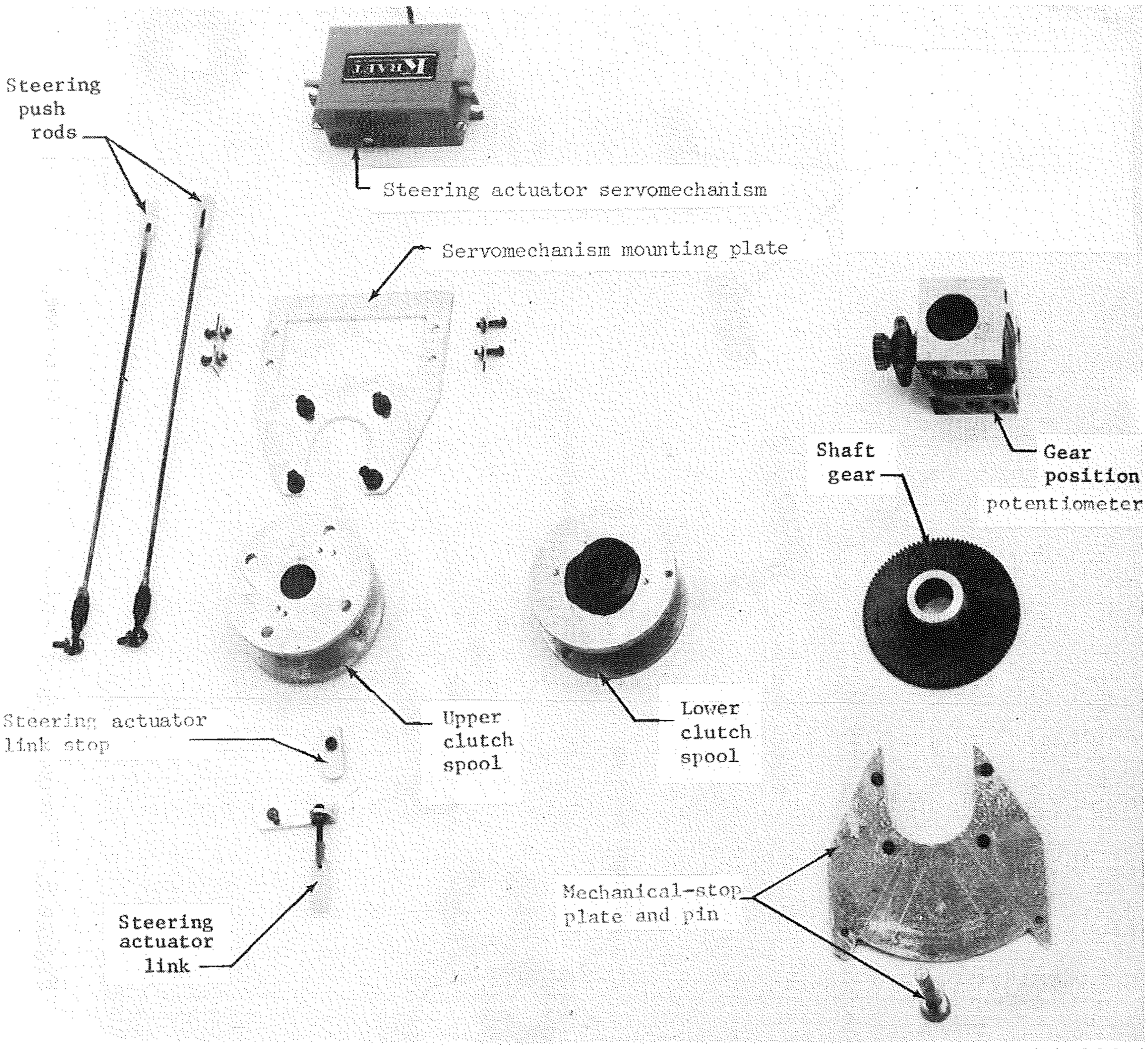
L-74-288.1

Figure 3.- Model landing gear assembly.



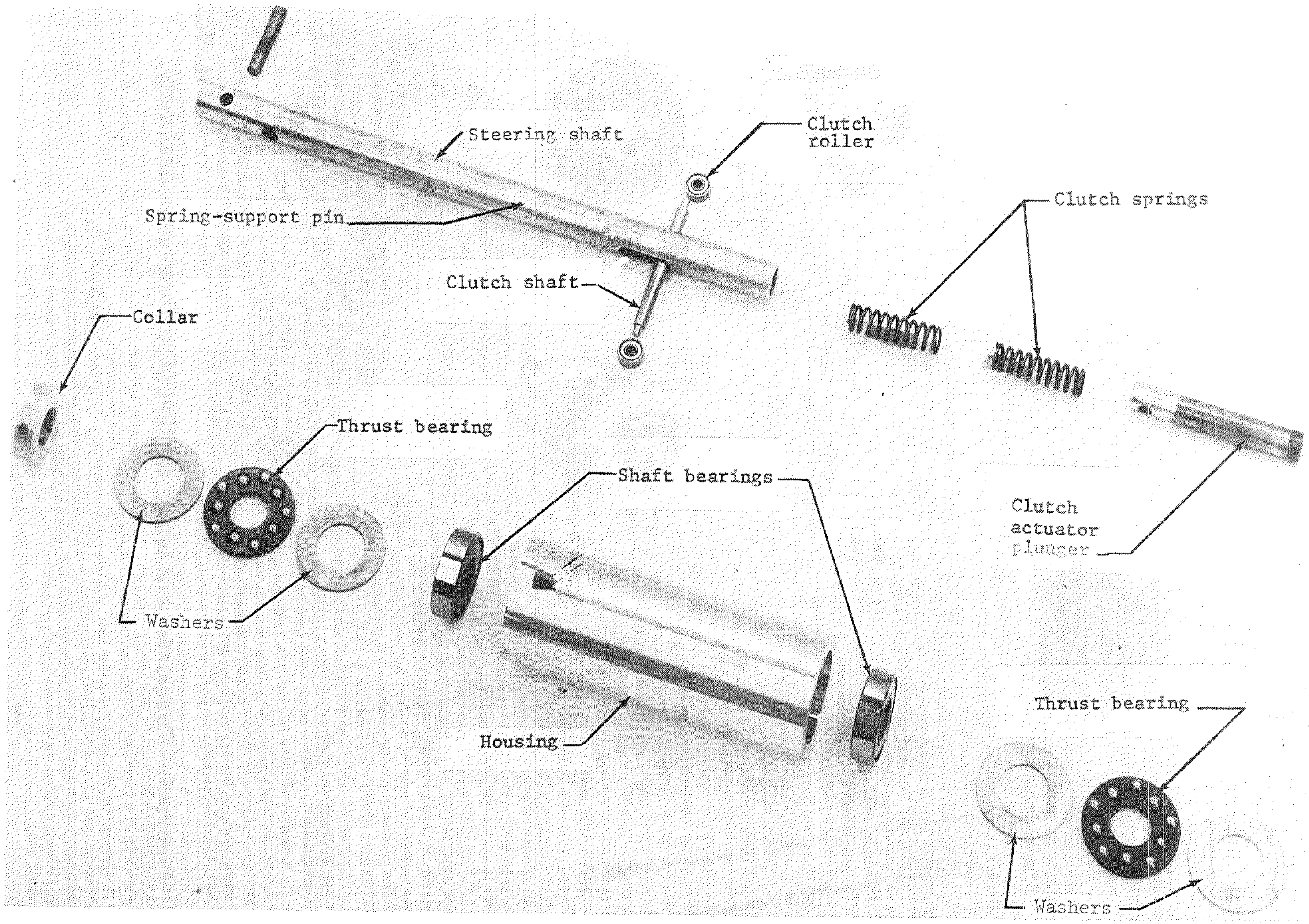
L-74-290.1

Figure 4.- Upper and midsections of landing-gear assembly.



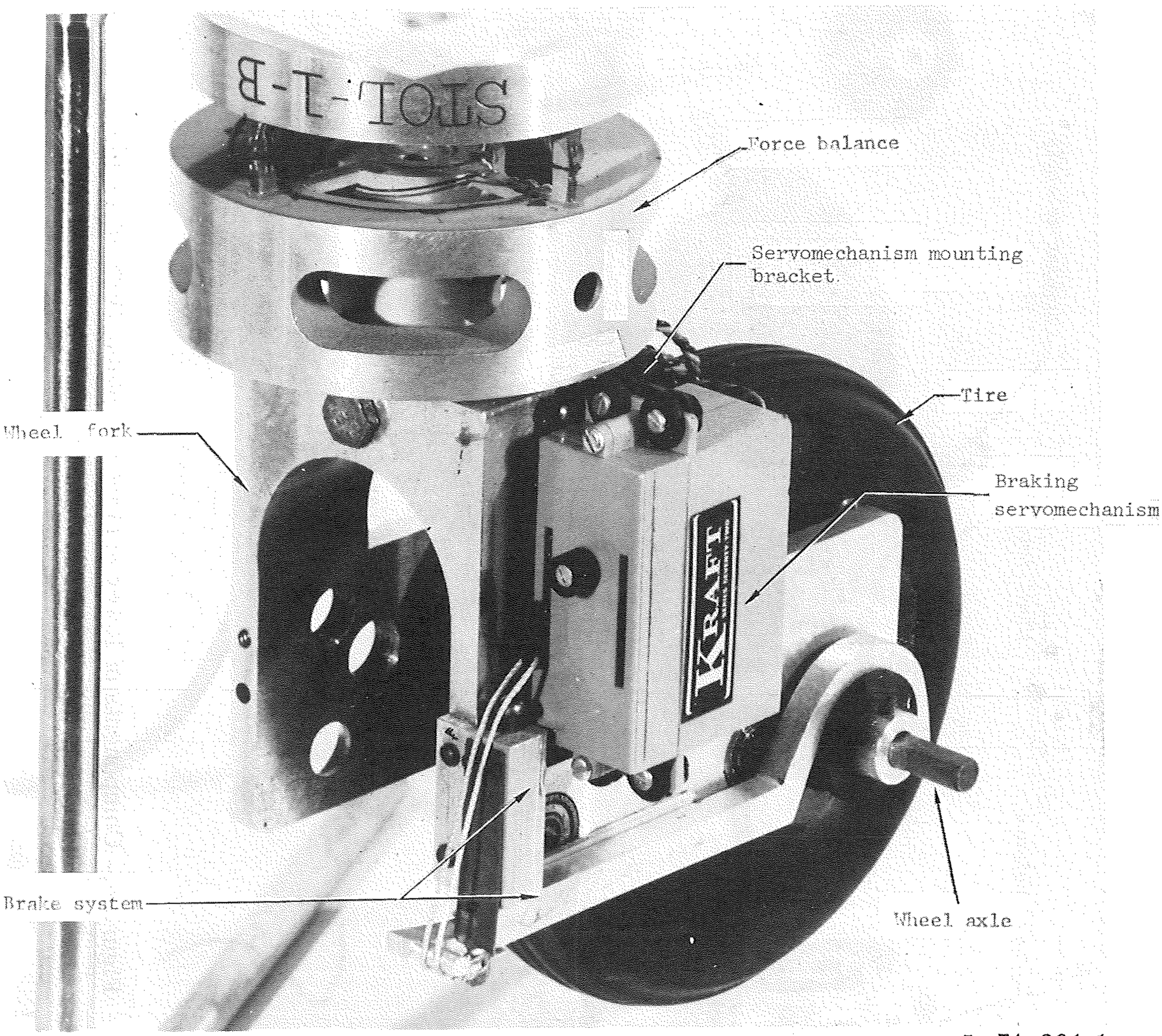
L-74-286.1

Figure 5.- Components of upper section of landing-gear assembly.



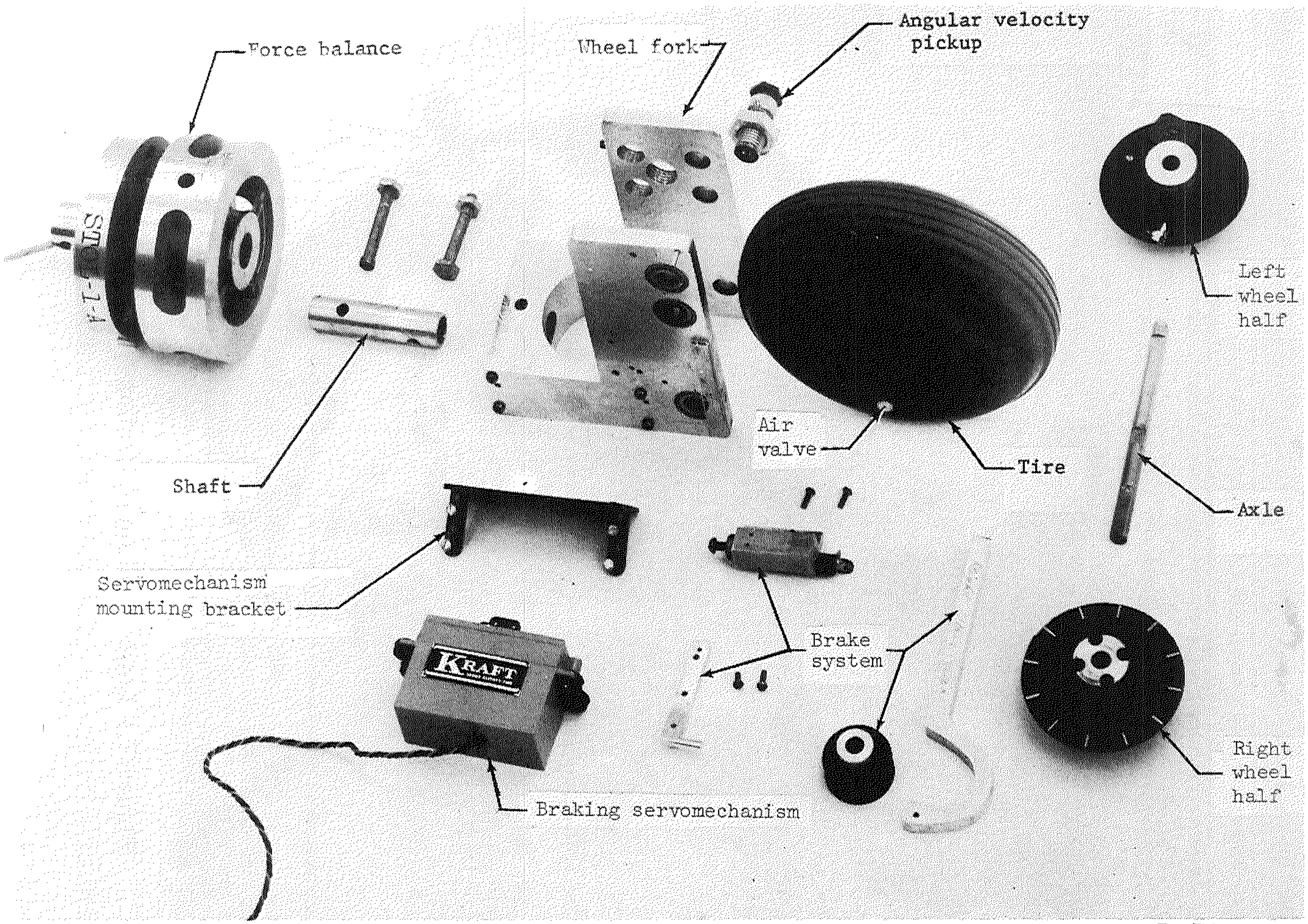
L-74-284.1

Figure 6.- Components of midsection of landing-gear assembly.



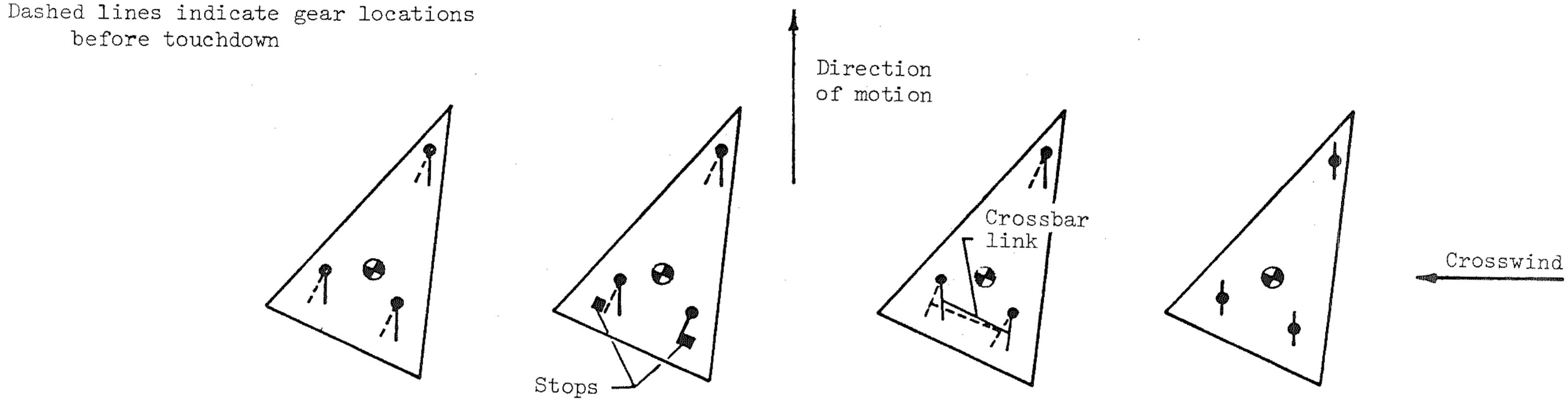
L-74-291.1

Figure 7.- Lower section of landing-gear assembly.



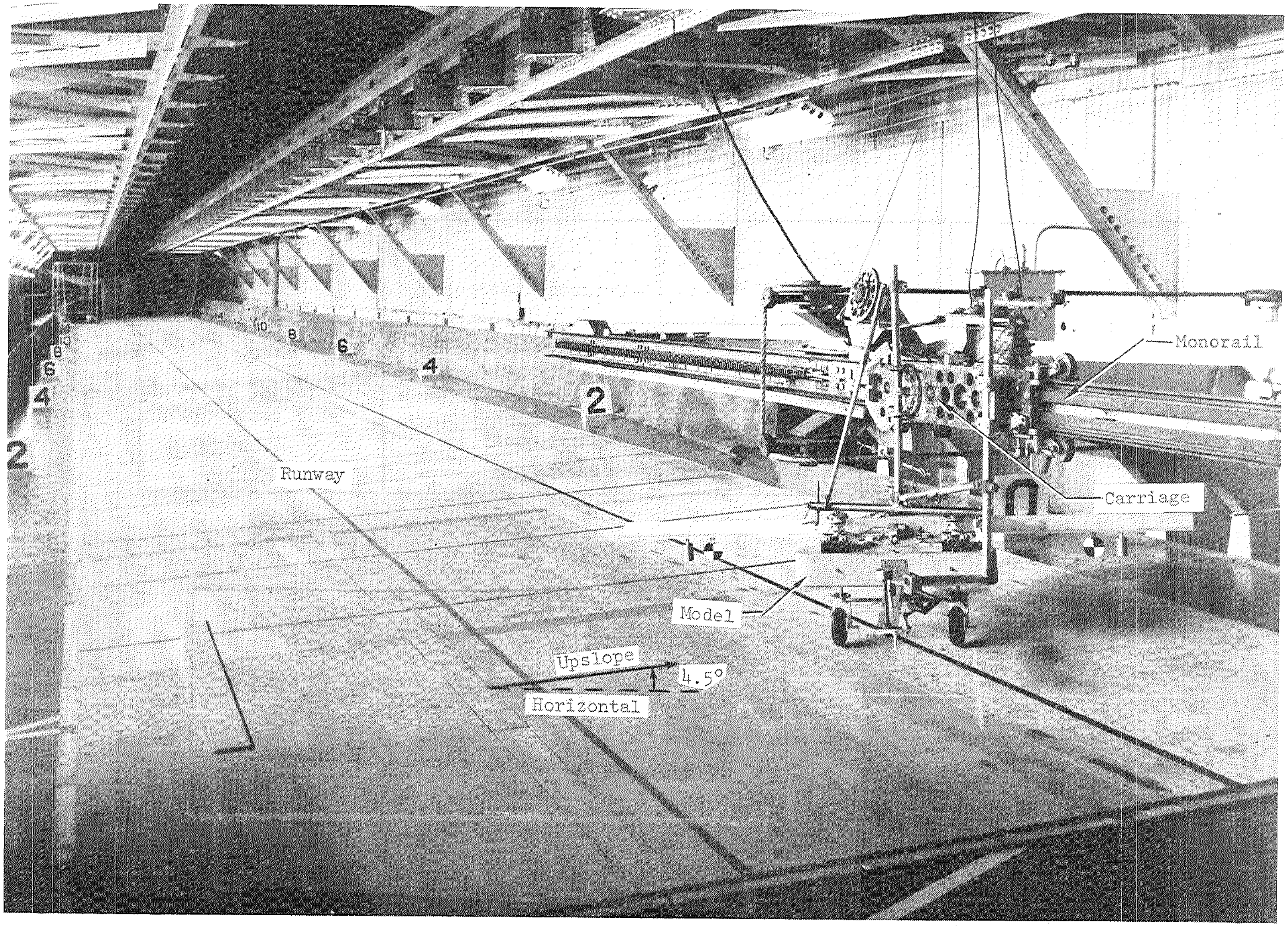
L-74-285.1

Figure 8.- Components of lower section of landing-gear assembly.



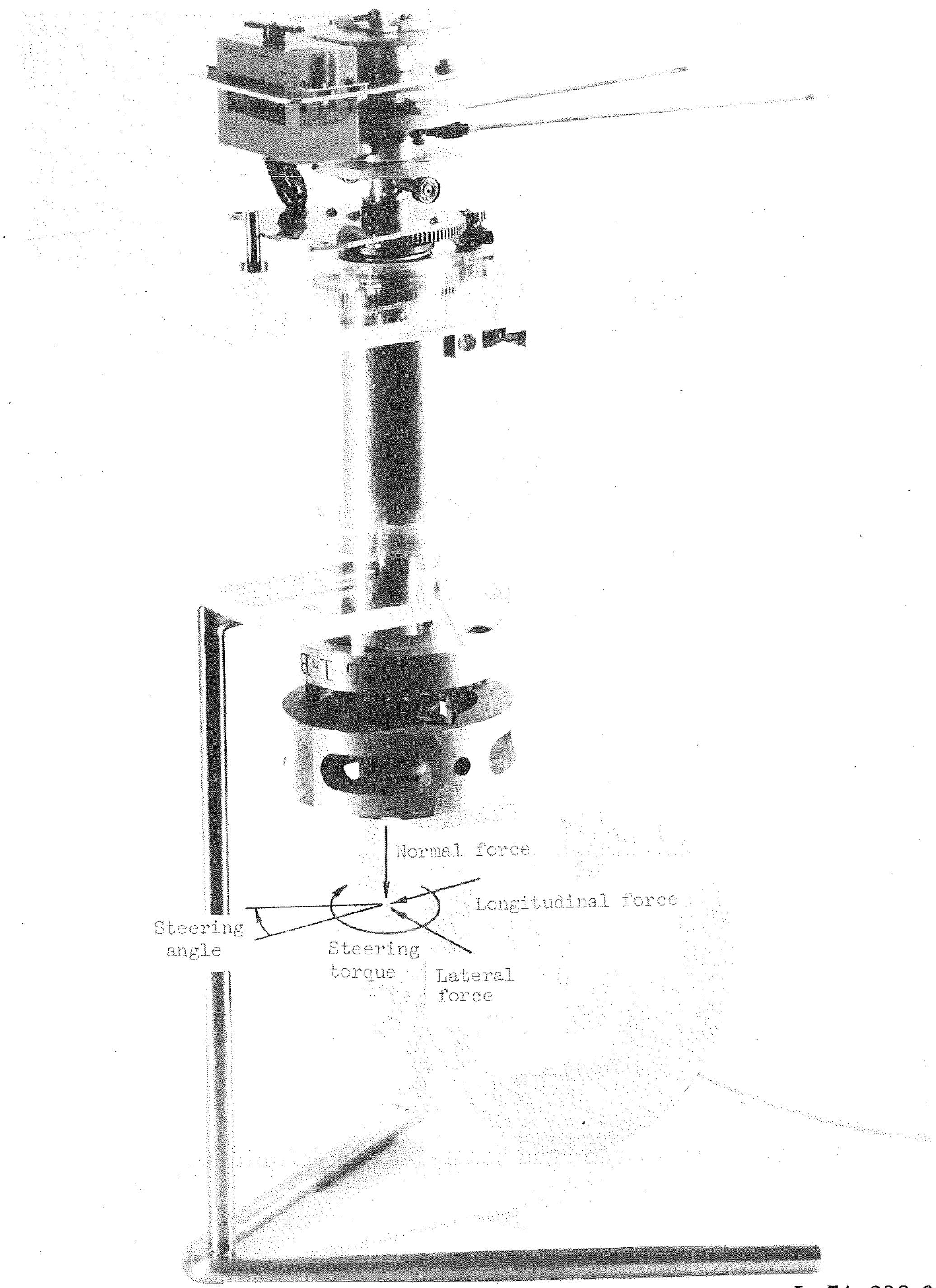
Concept	A	B	C	D
Prior to touchdown	All gears free to swivel	Nose gear free to swivel; main-gear swivel direction limited	Nose gear free to swivel; main-gear swivel together with toeout	All gears set to crab angle
During rollout	Nose or all gears steerable	Nose-gear steering only	Nose-gear steering only	Nose or all gears steerable

Figure 9.- Crosswind gear concepts.



L-73-757.1

Figure 10.- Runway and launch apparatus.



L-74-288.2

Figure 11.- Positive direction of gear forces.

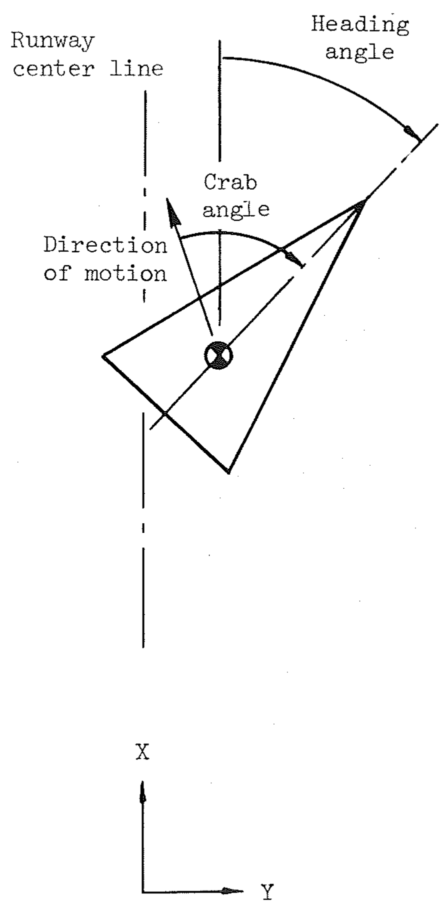
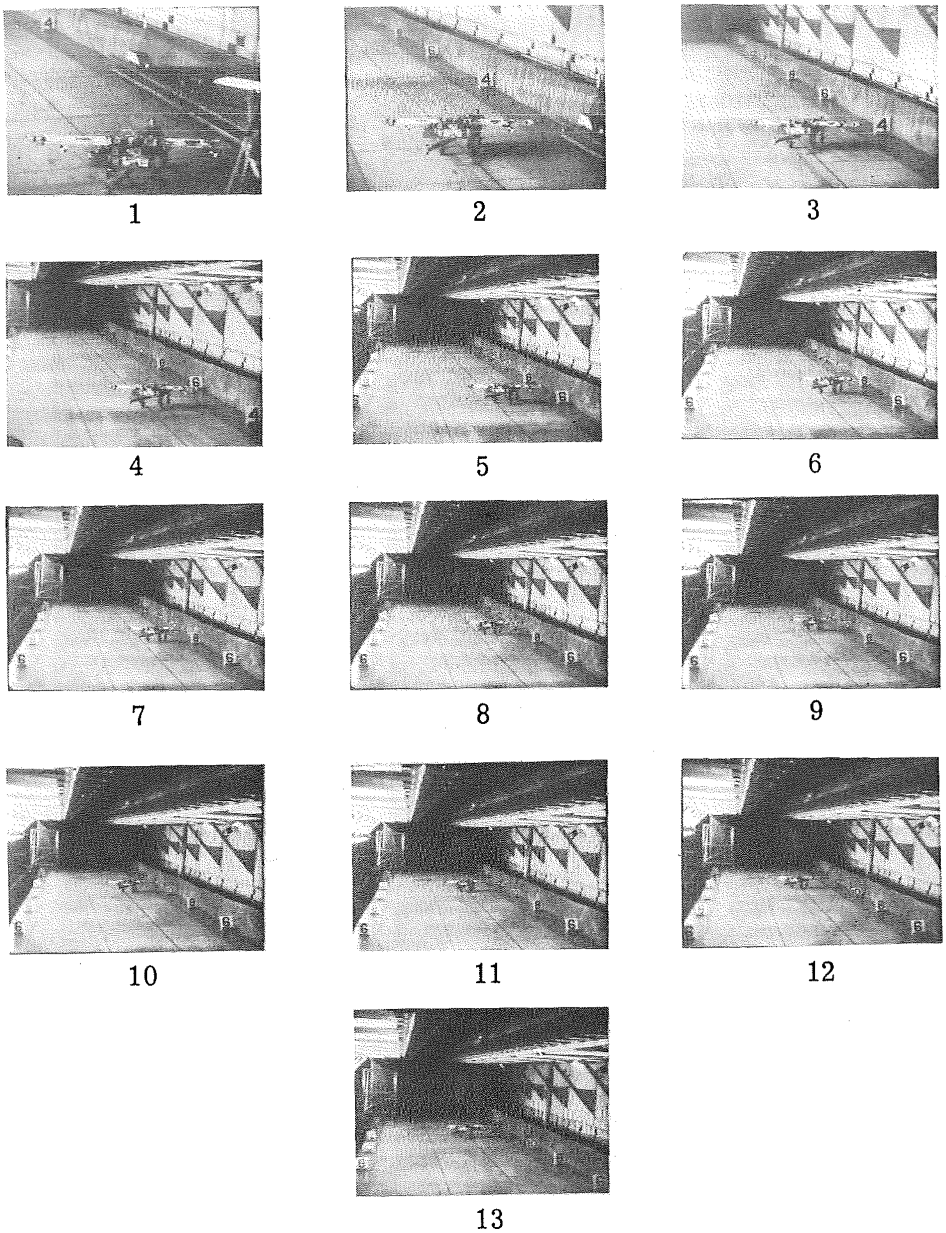


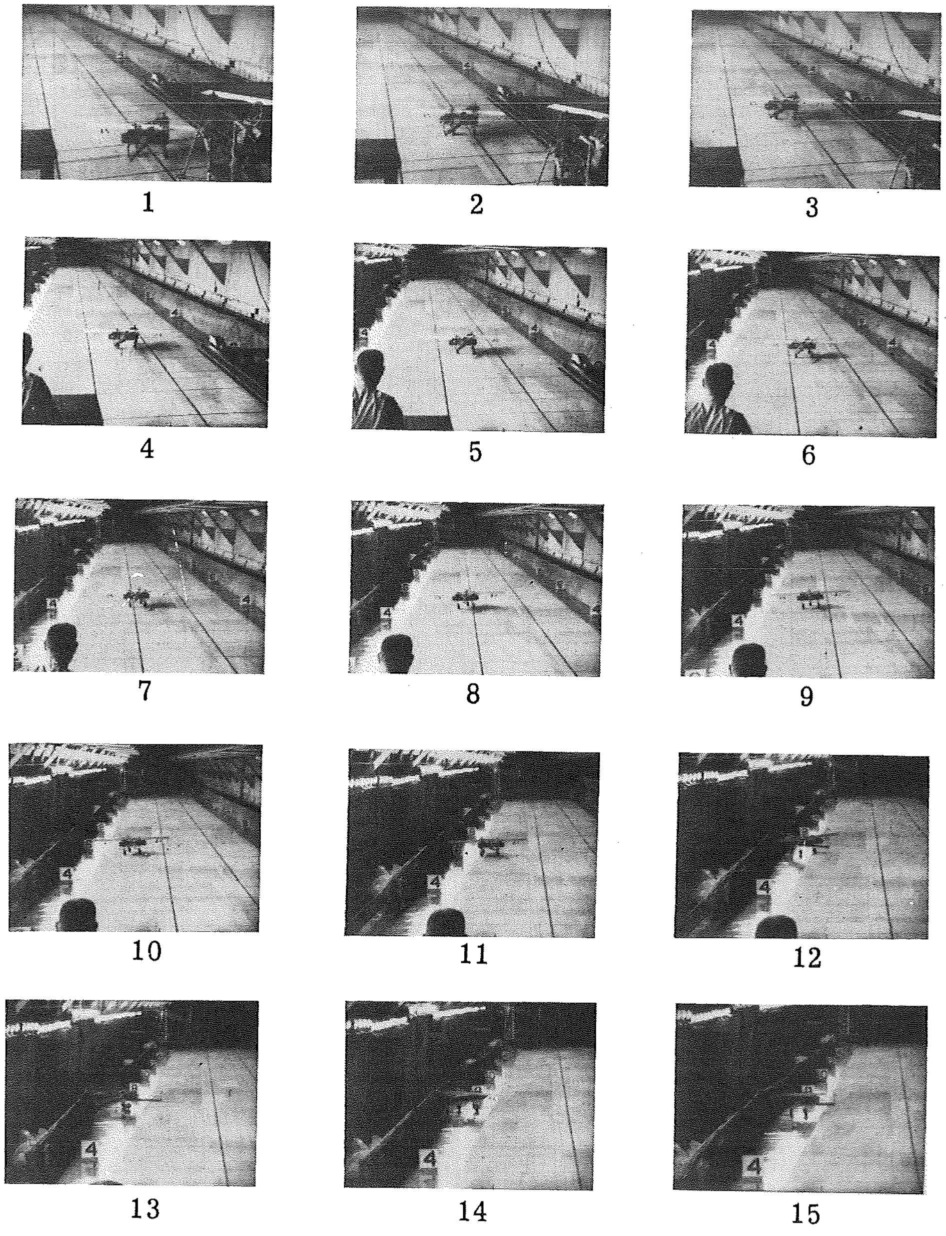
Figure 12.- Crab- and heading-angle definitions.



L-75-129

(a) Nose-gear steering only.

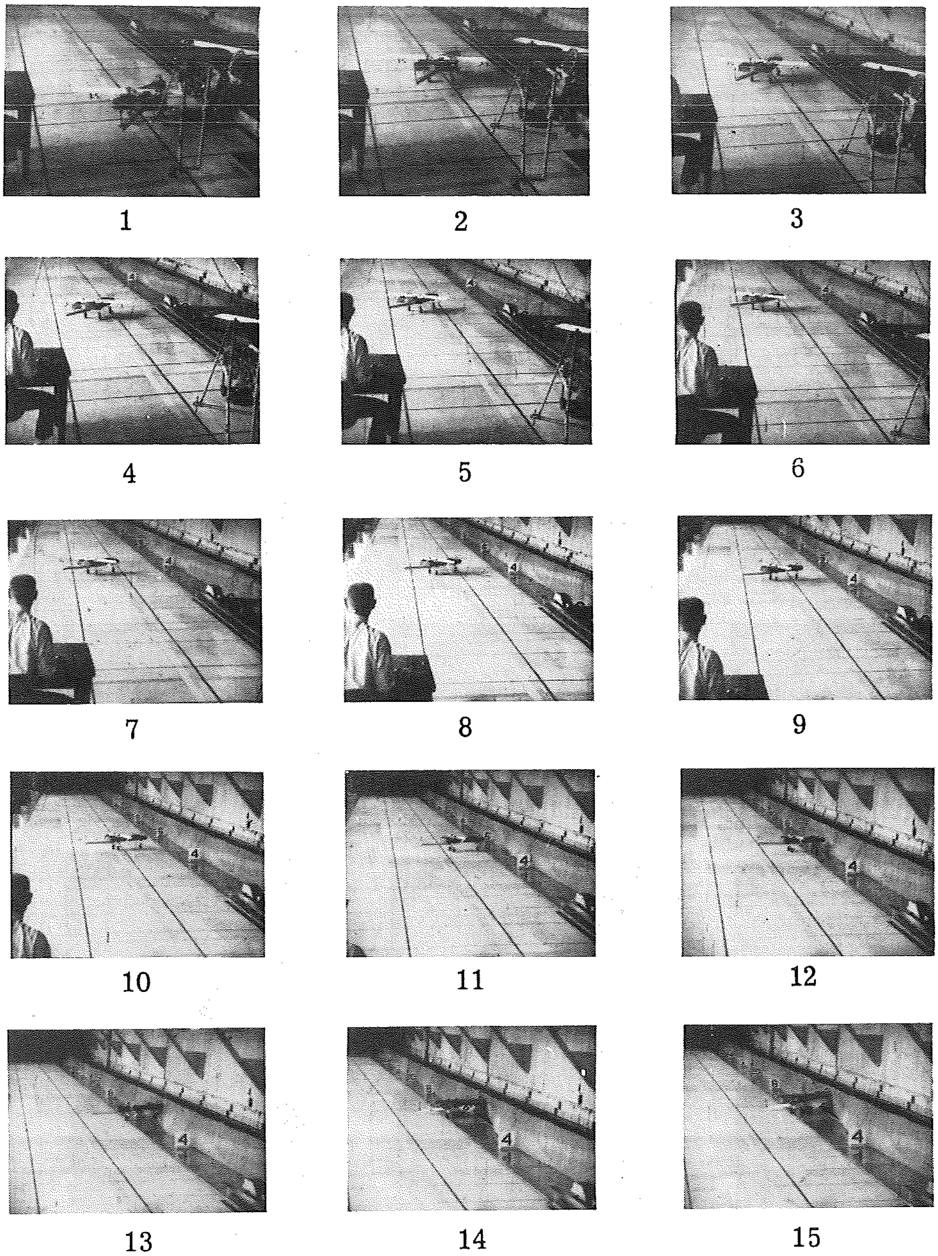
Figure 13.- Sequence photographs of landing runout for model with concept A.



L-75-130

(b) Steering all gears together.

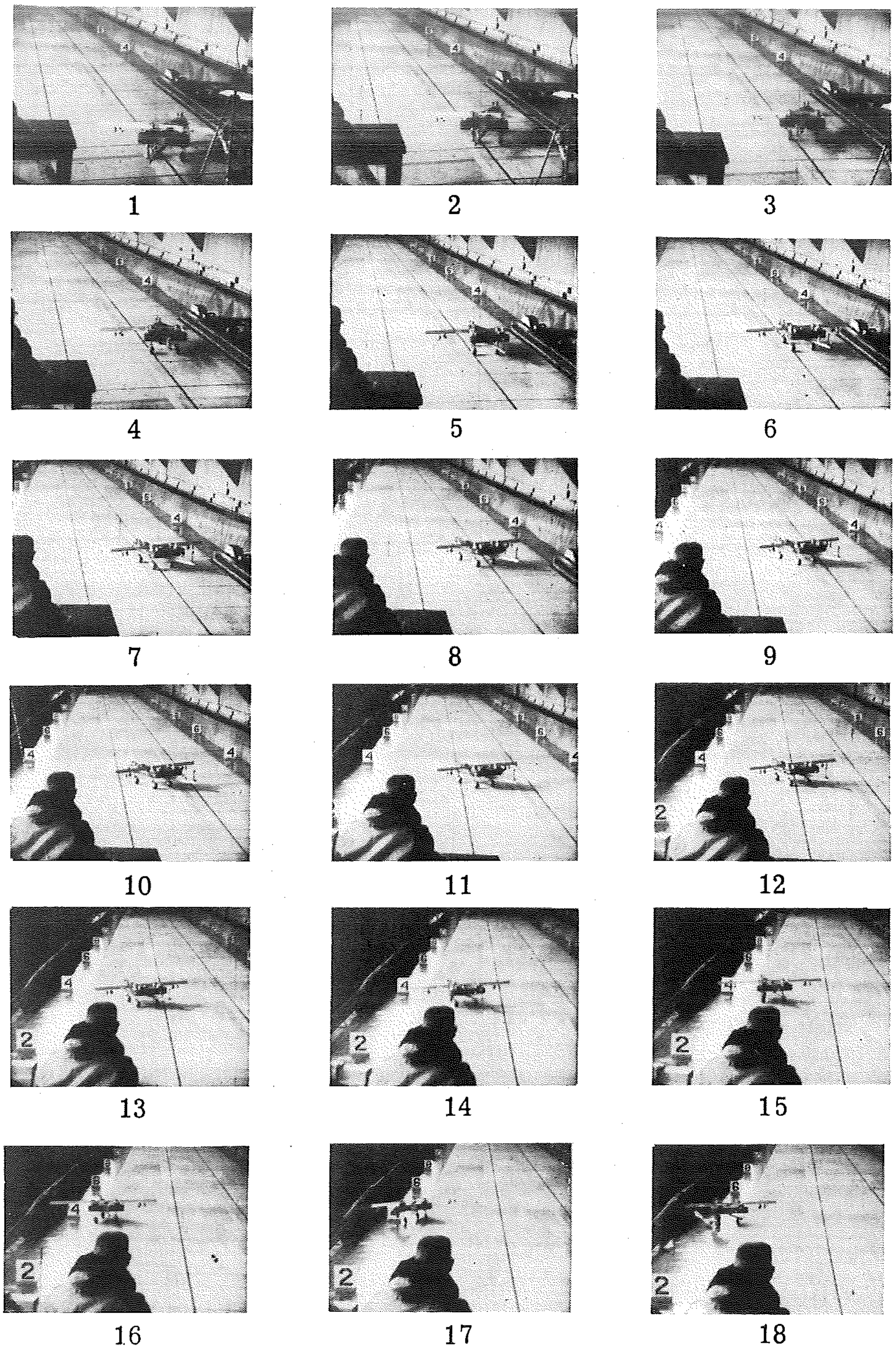
Figure 13.- Continued.



L-75-131

(c) Independent steering of nose and main gears.

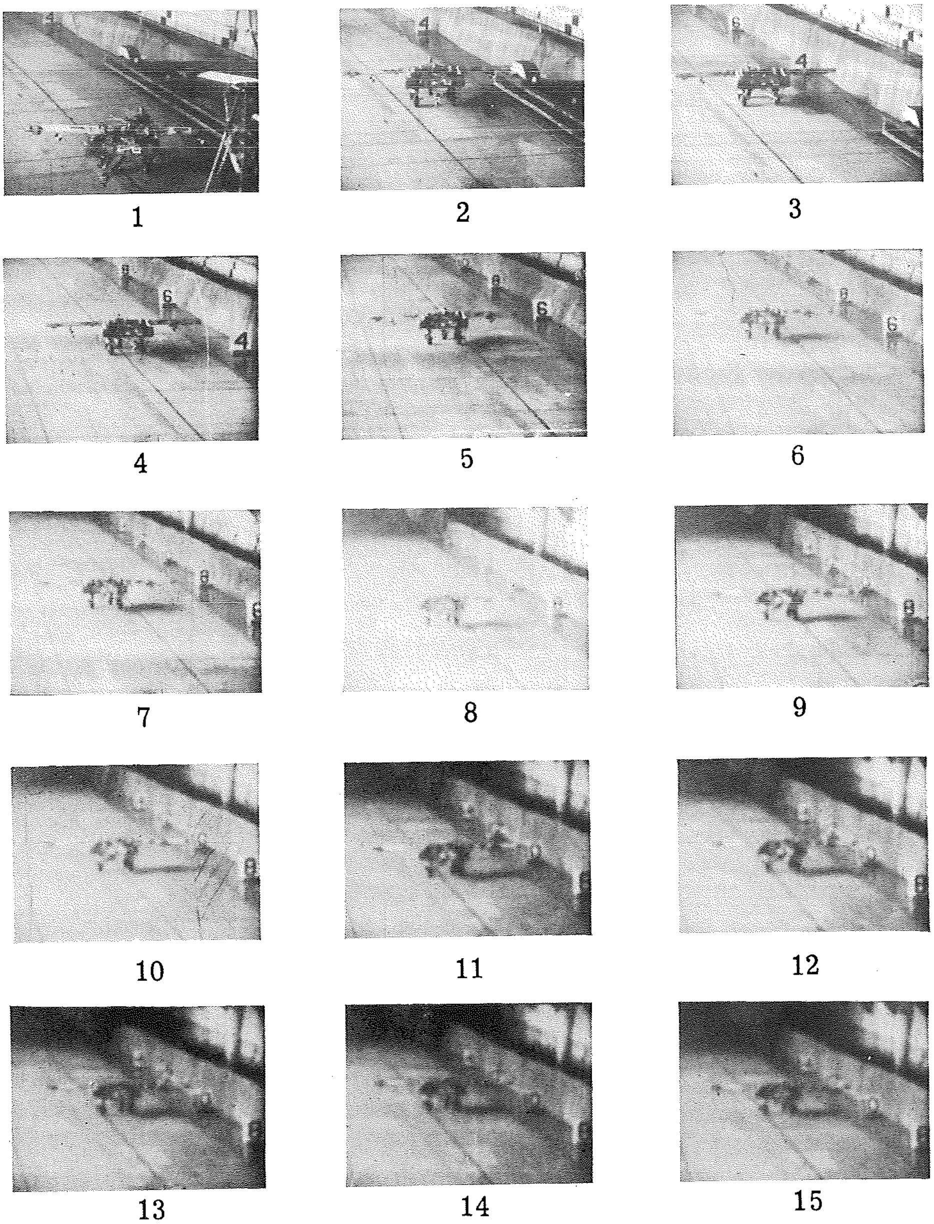
Figure 13.- Concluded.



L-75-132

(a) Steering actuated after touchdown.

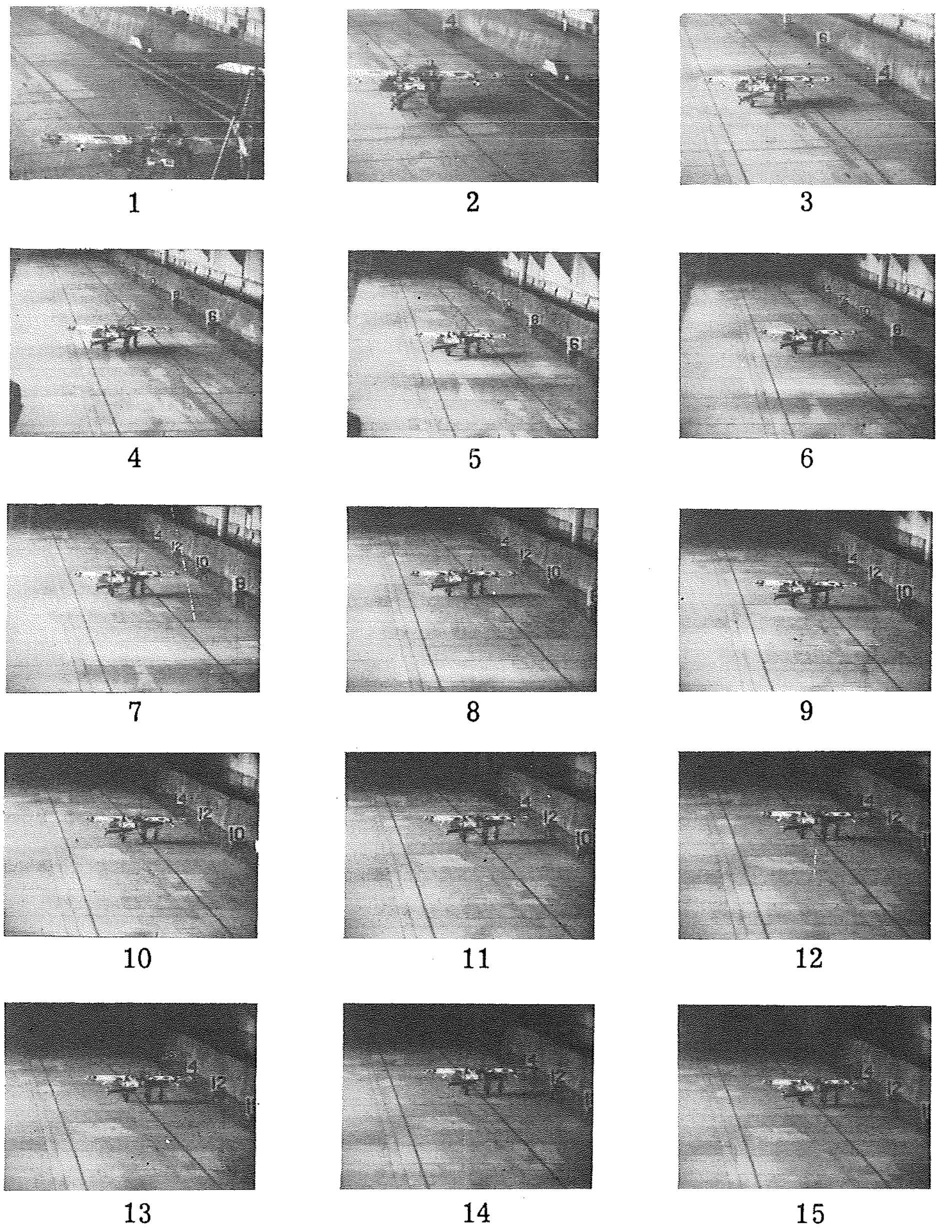
Figure 14.- Sequence photographs of landing runout for model with concept B.



L-75-133

(b) Steering actuated prior to touchdown.

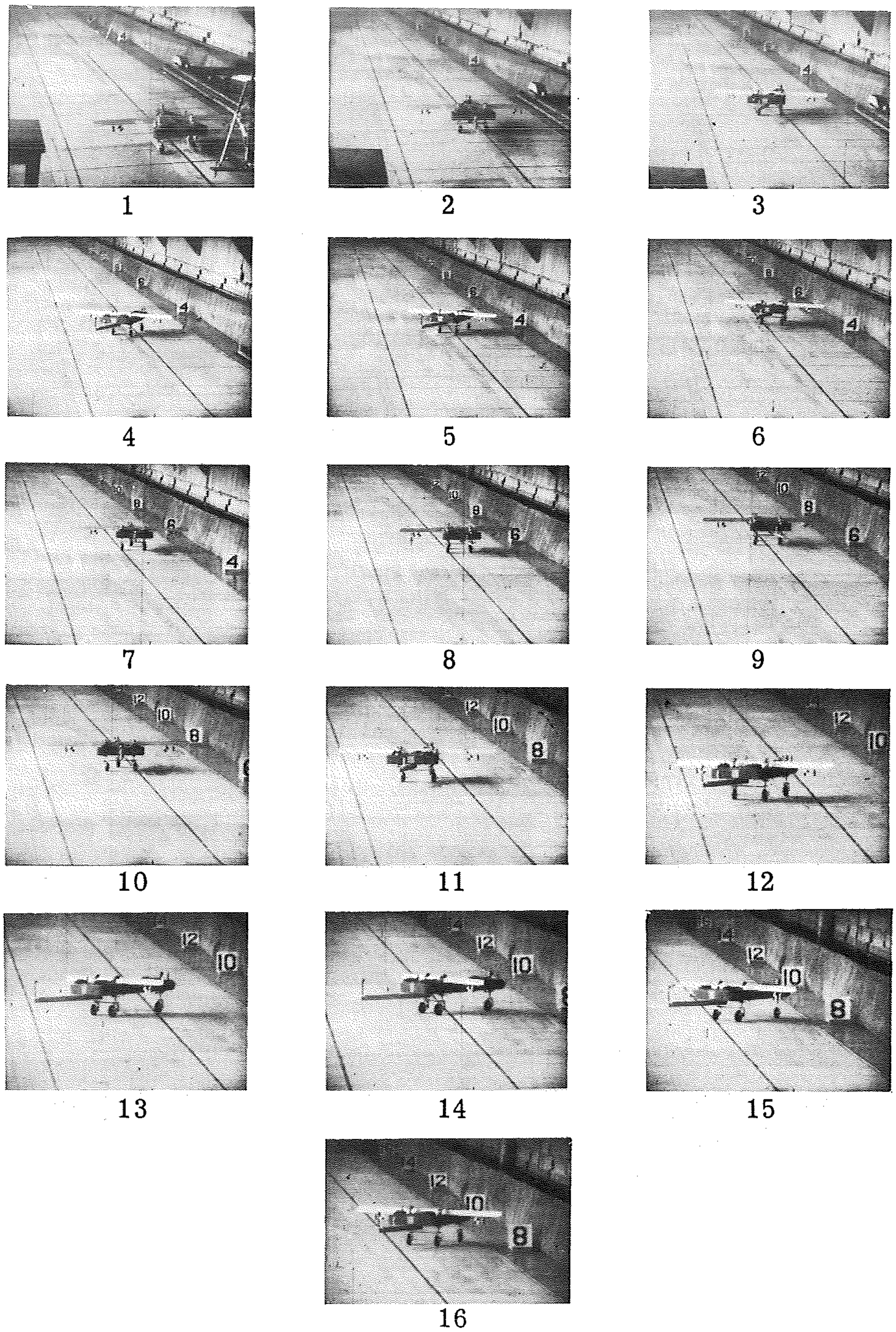
Figure 14.- Concluded.



L-75-134

(a) Model landed at 30° crab.

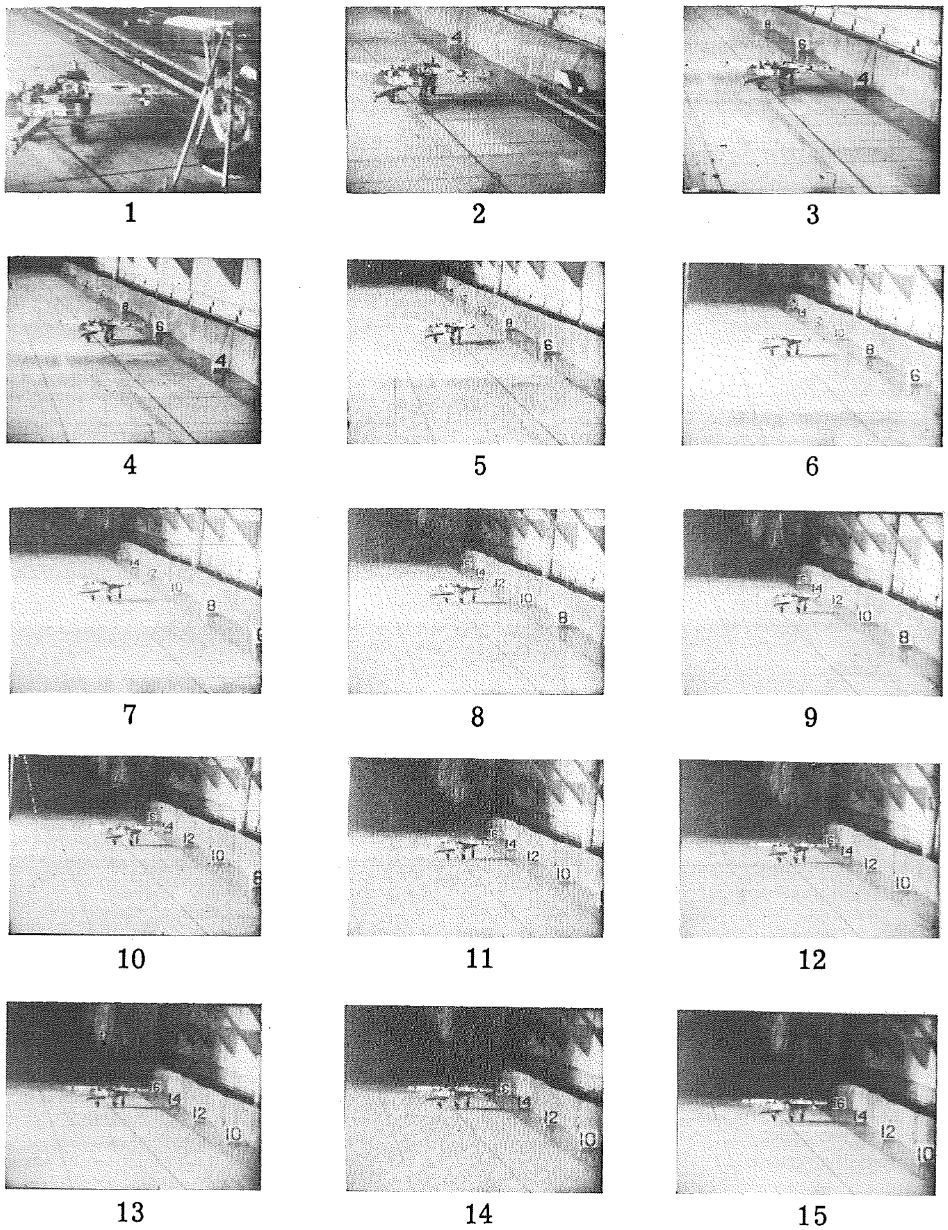
Figure 15.- Sequence photographs of the landing runout for model with concept C.



L-75-135

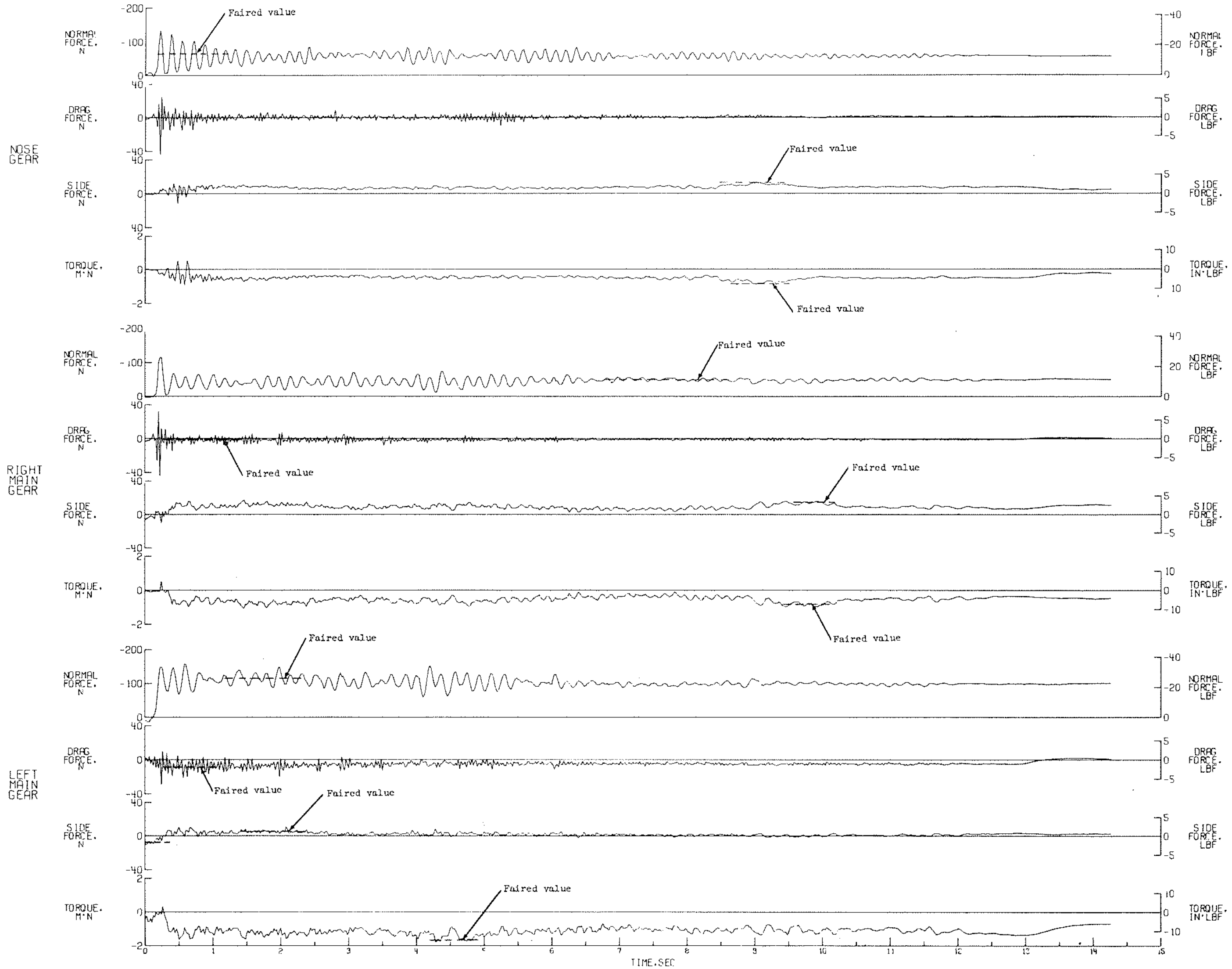
(b) Model landed at 0° crab.

Figure 15.- Concluded.



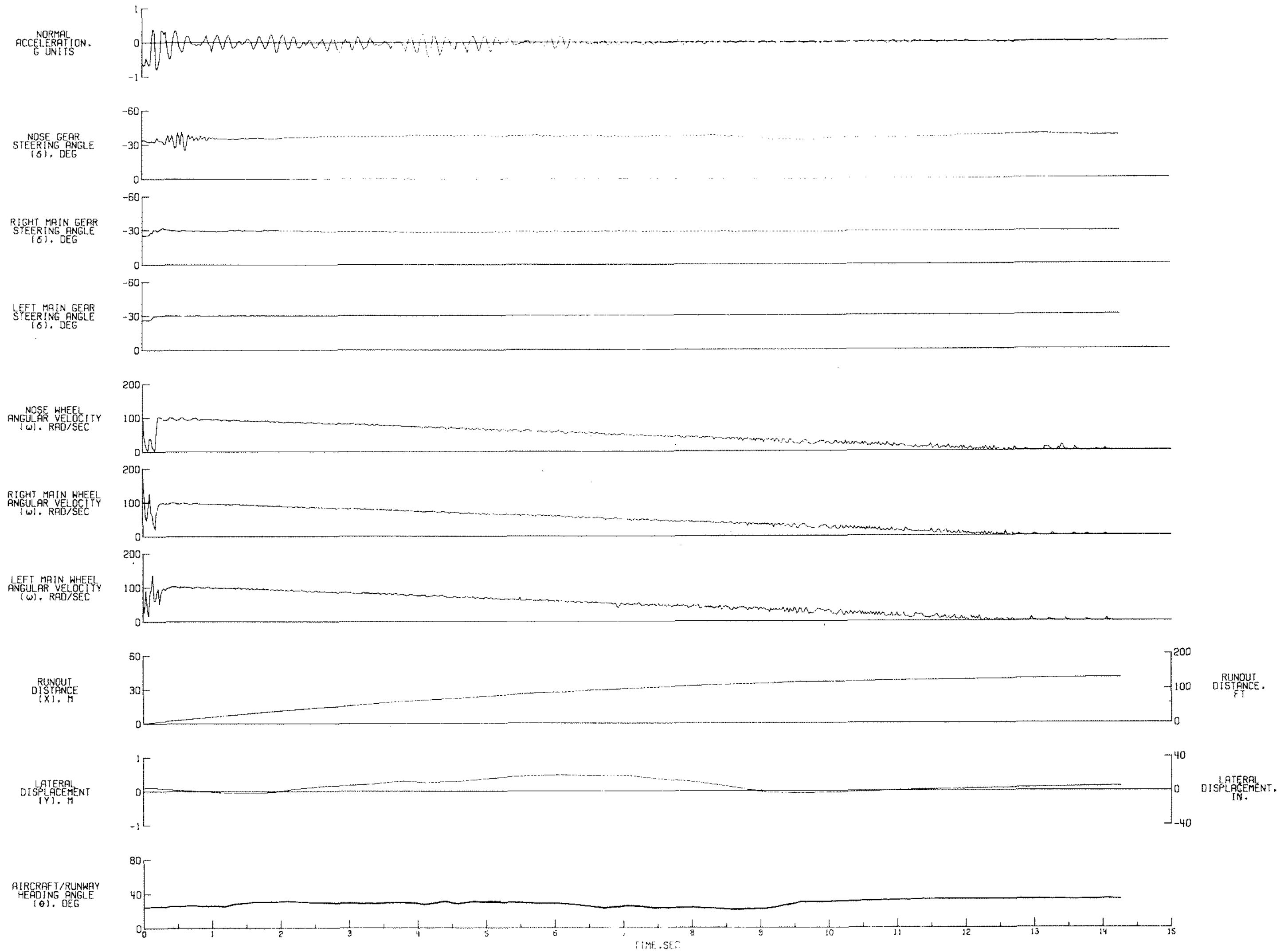
L-75-136

Figure 16.- Sequence photographs of typical landing runout for model with concept D.



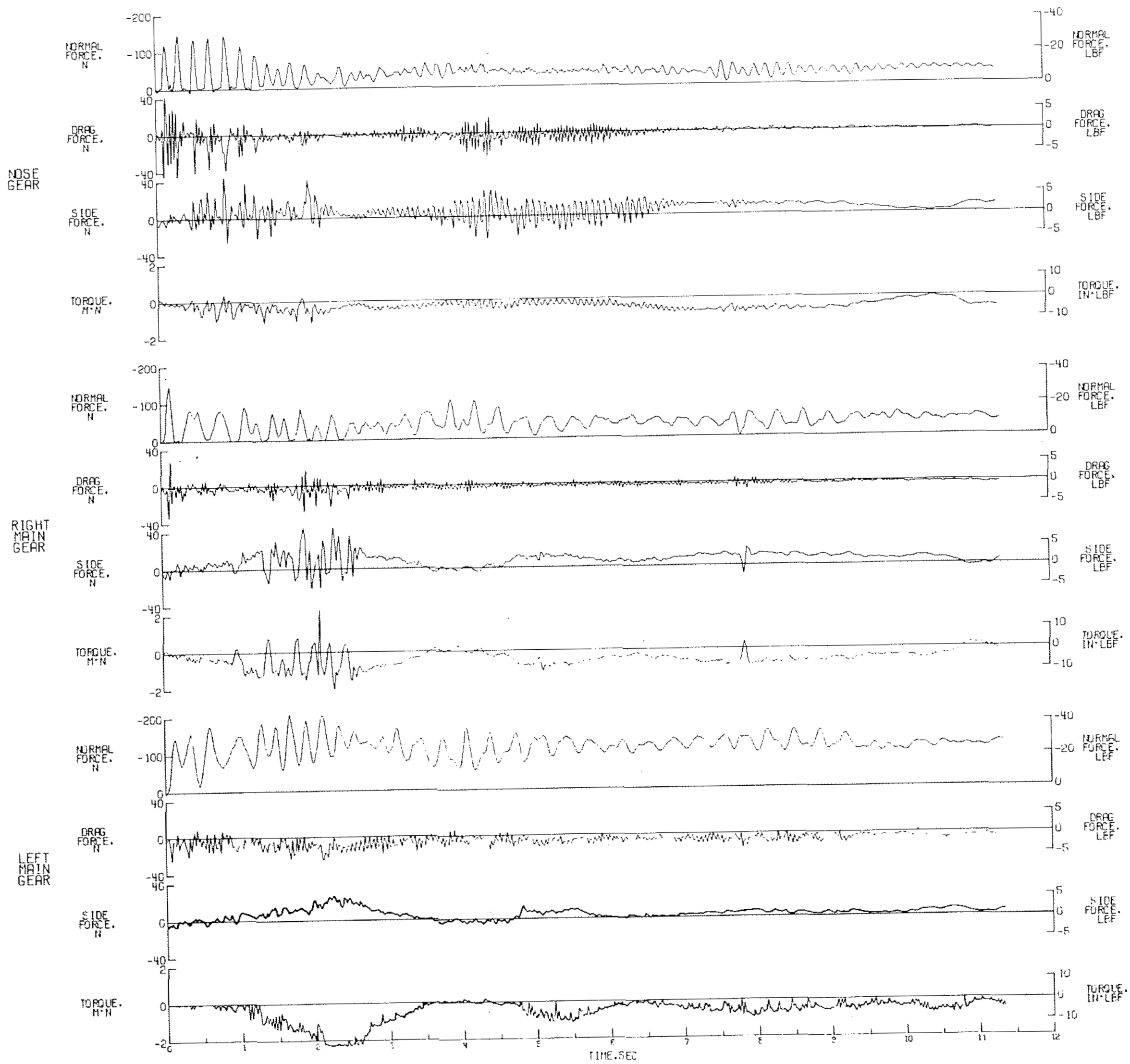
(a) Gear forces.

Figure 17.- Time histories of case 1 (concept A).



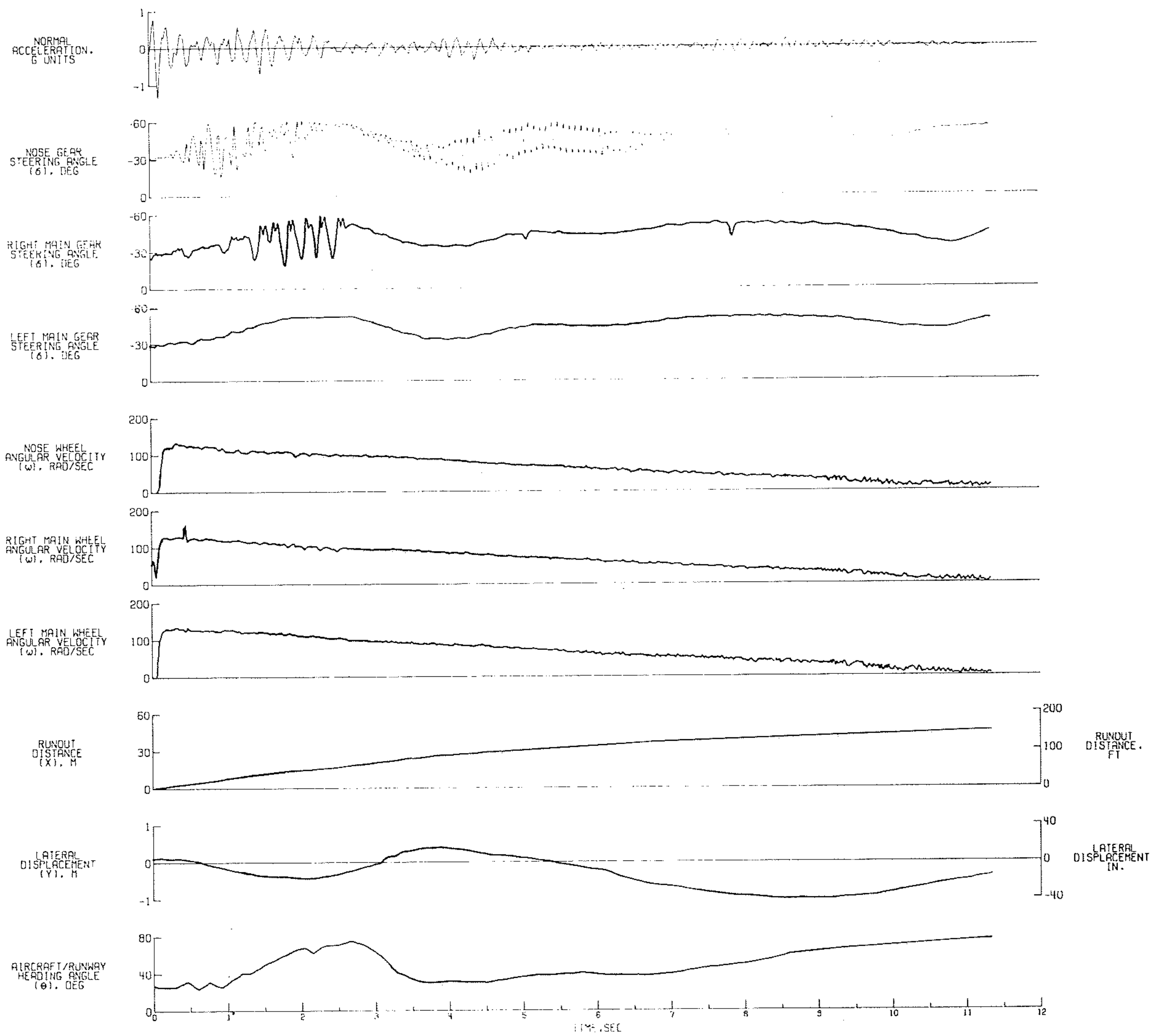
(b) Gear steering angles, wheel speeds, and vehicle-trajectory parameters.

Figure 17.- Concluded.



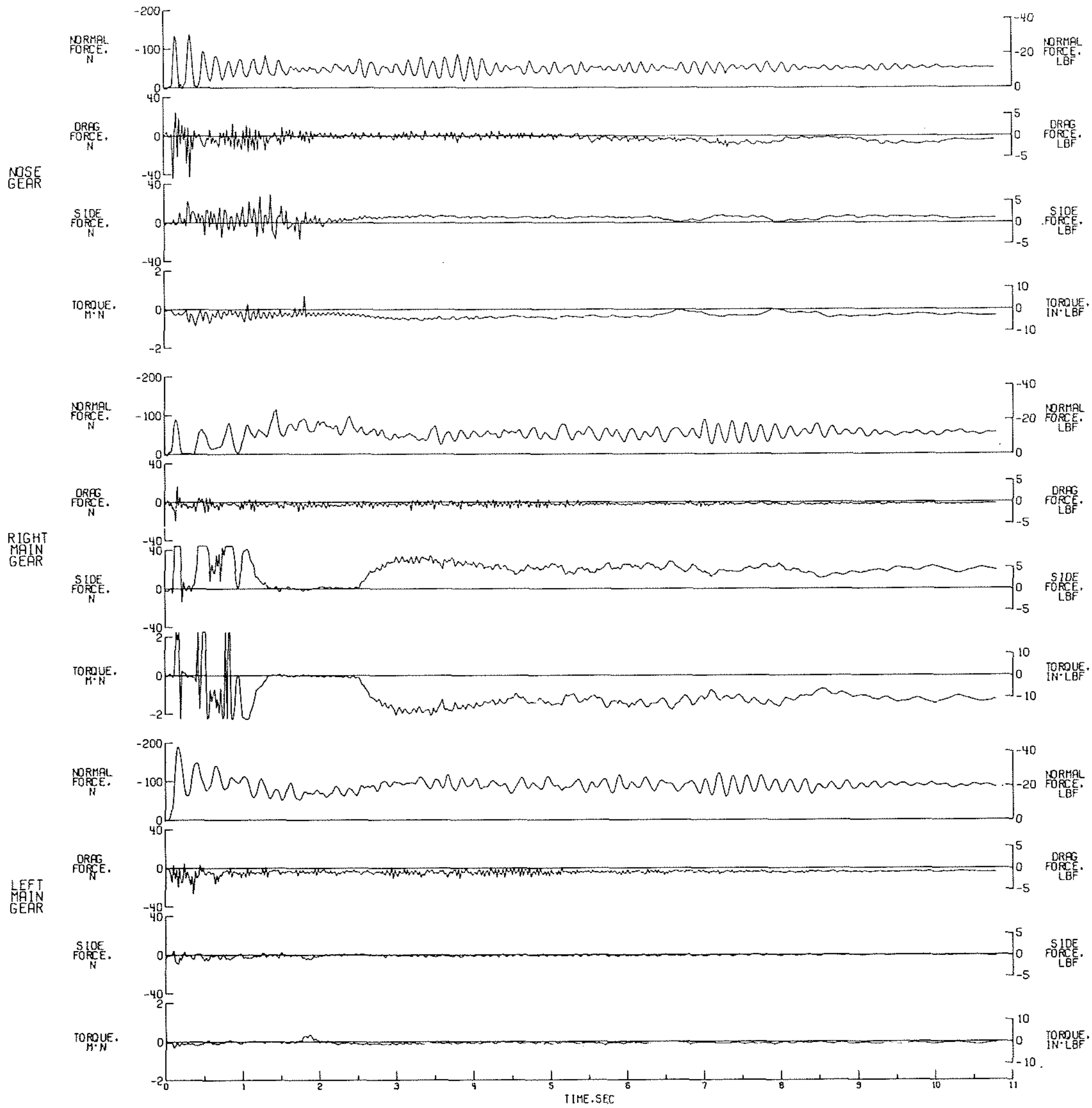
(a) Gear forces.

Figure 18.- Time histories of case 2 (concept A).



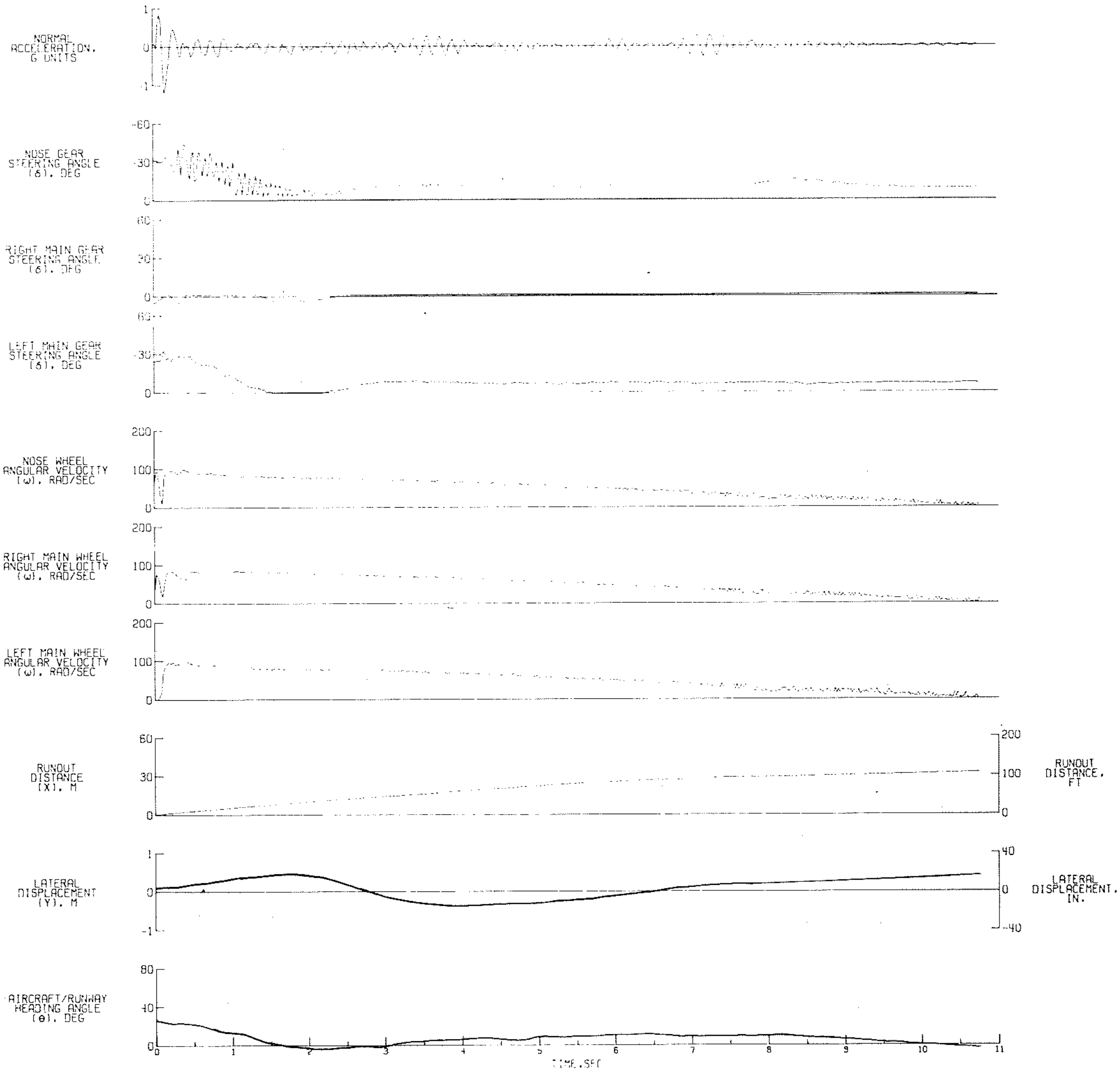
(b) Gear steering angles, wheel speeds, and vehicle-trajectory parameters.

Figure 18.- Concluded.



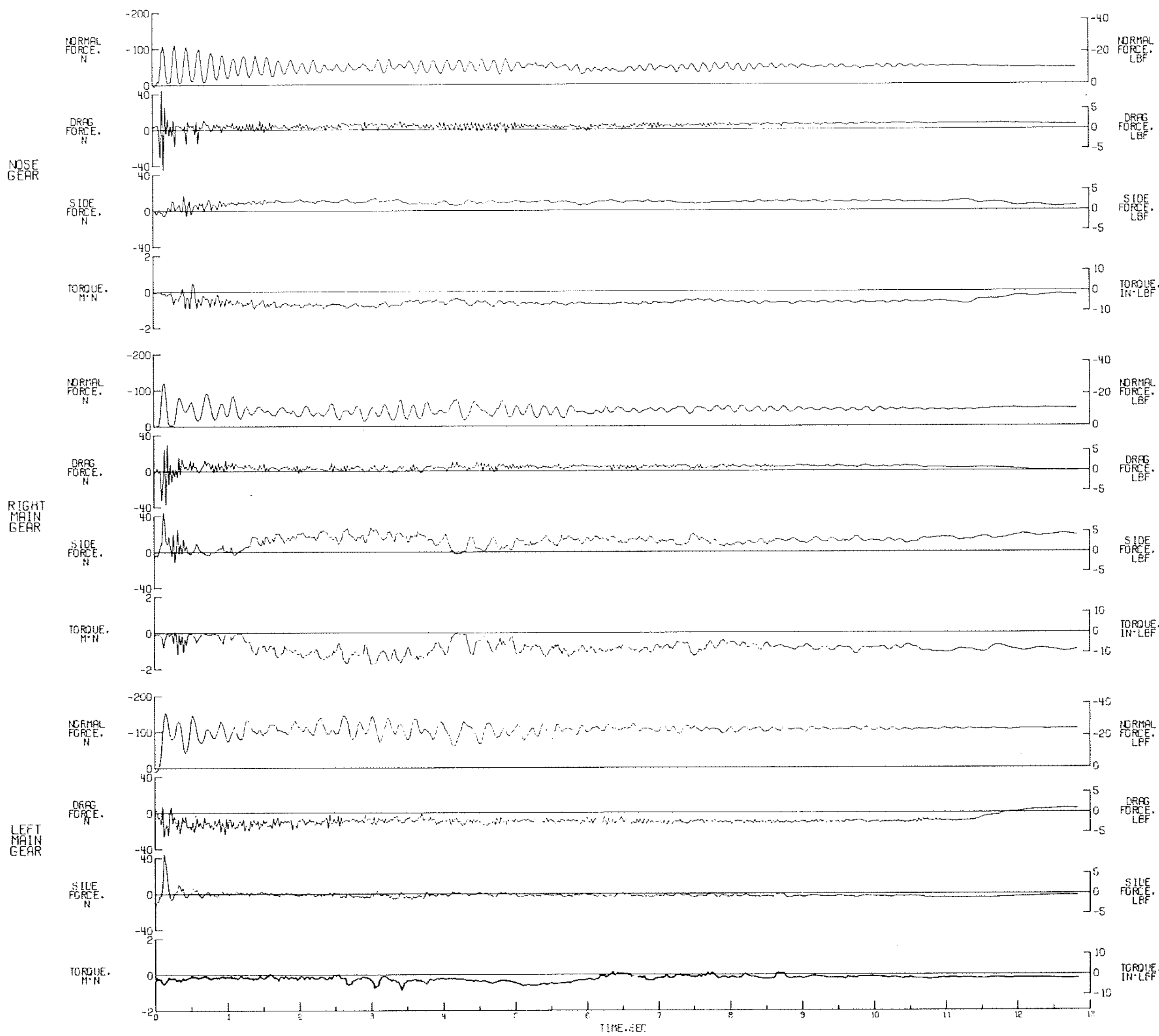
(a) Gear forces.

Figure 19.- Time histories of case 3 (concept B).



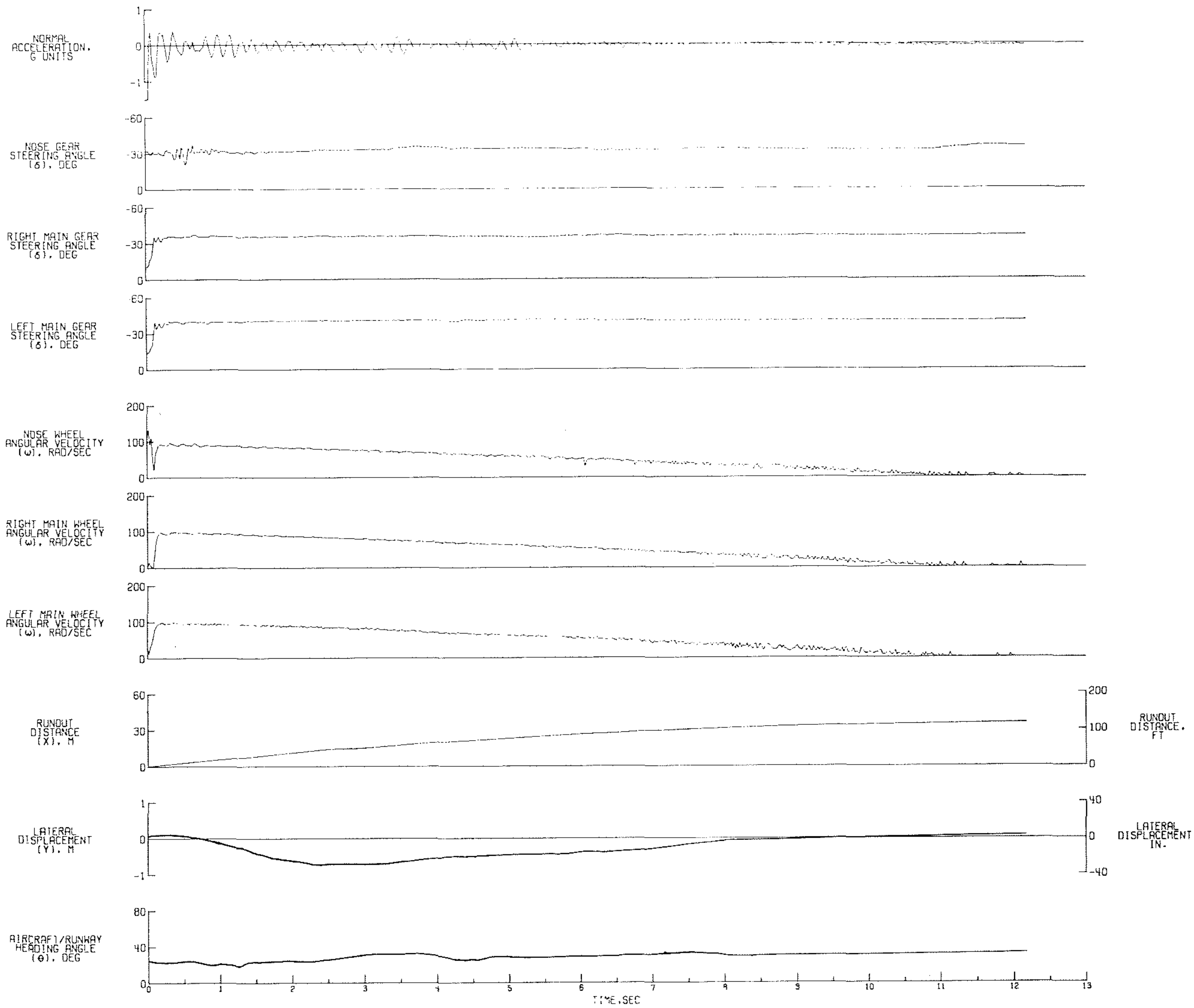
(b) Gear steering angles, wheel speeds, and vehicle-trajectory parameters.

Figure 19.- Concluded.



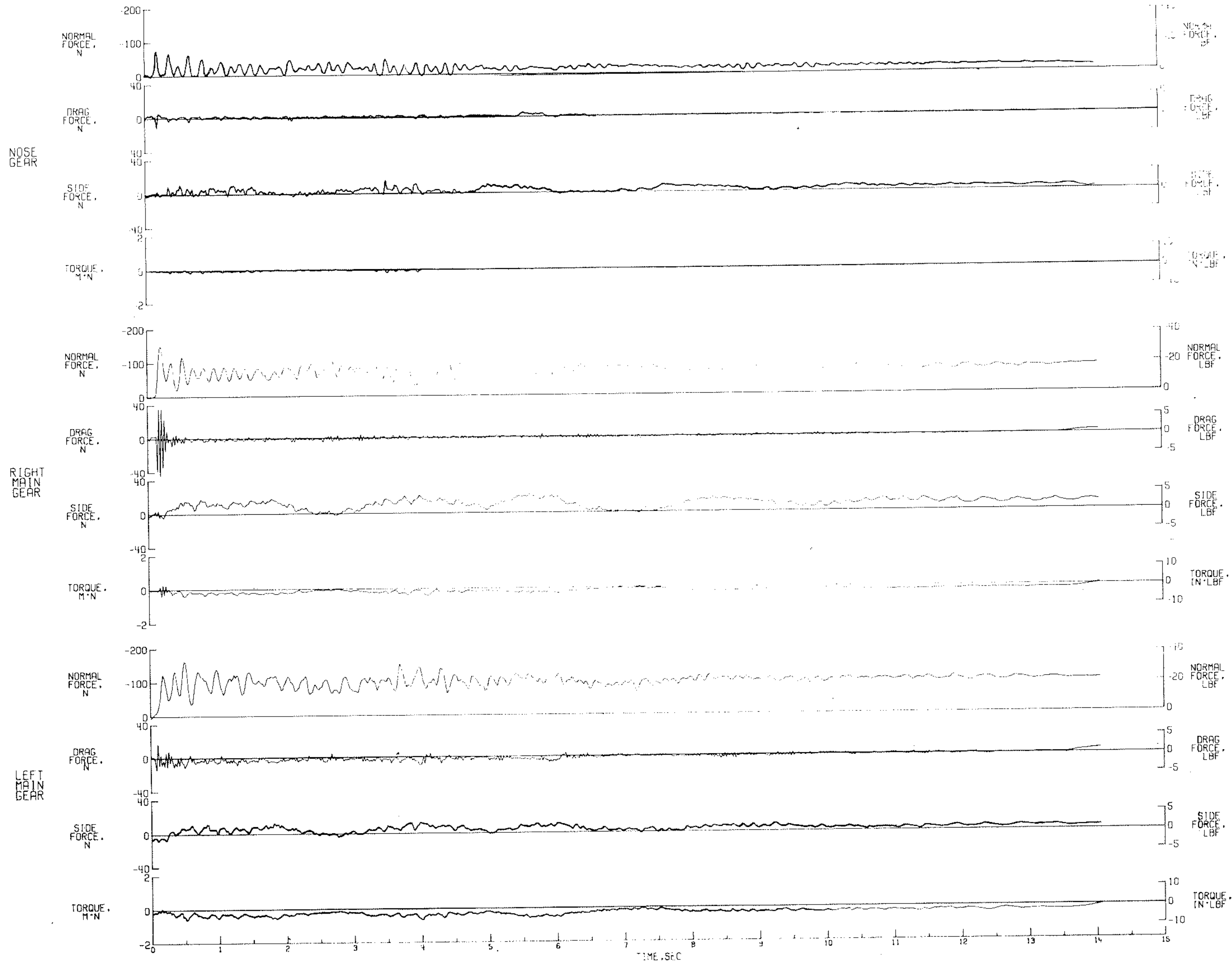
(a) Gear forces.

Figure 20.- Time histories of case 4 (concept C).



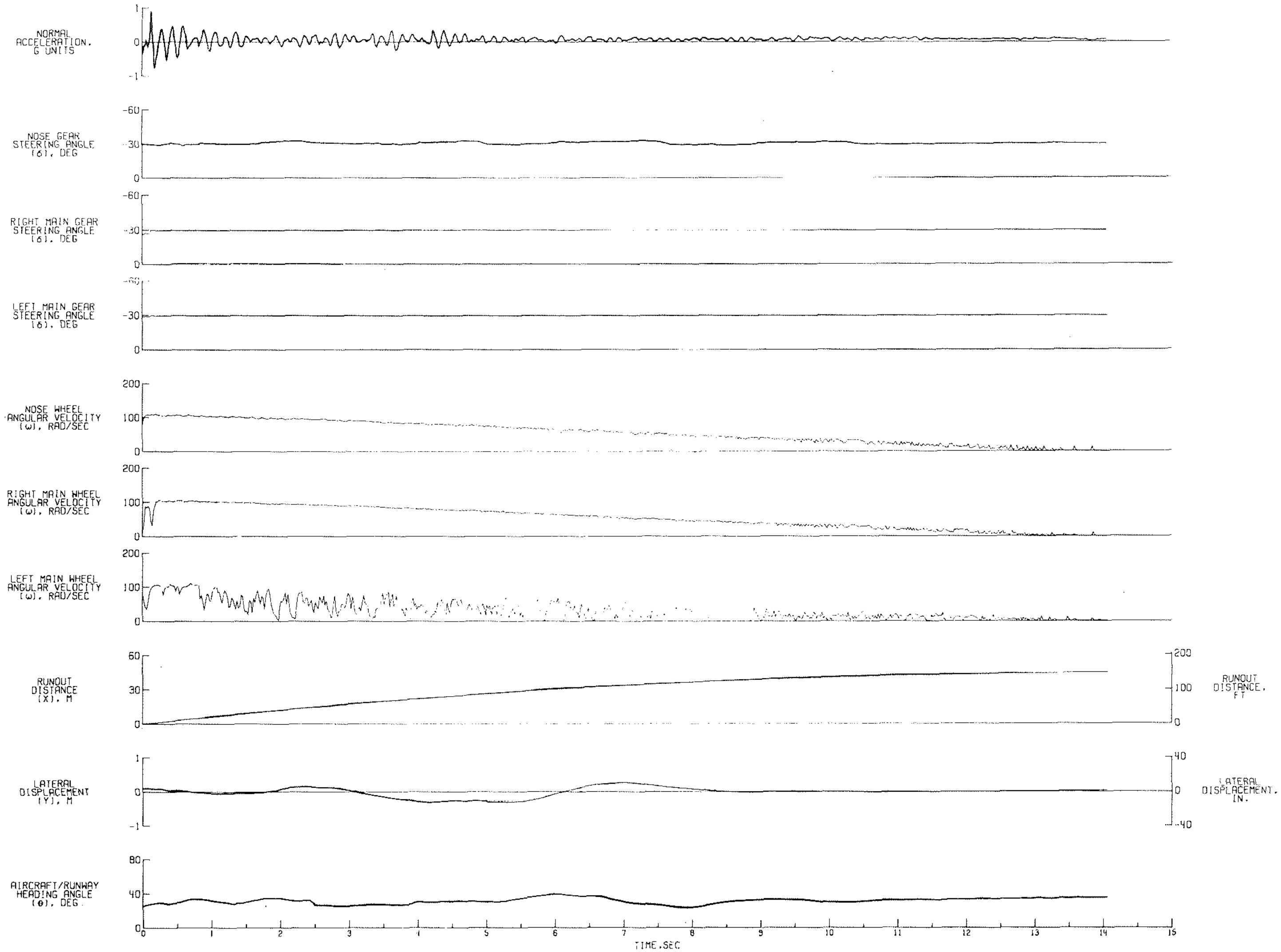
(b) Gear steering angles, wheel speeds, and vehicle-trajectory parameters.

Figure 20.- Concluded.



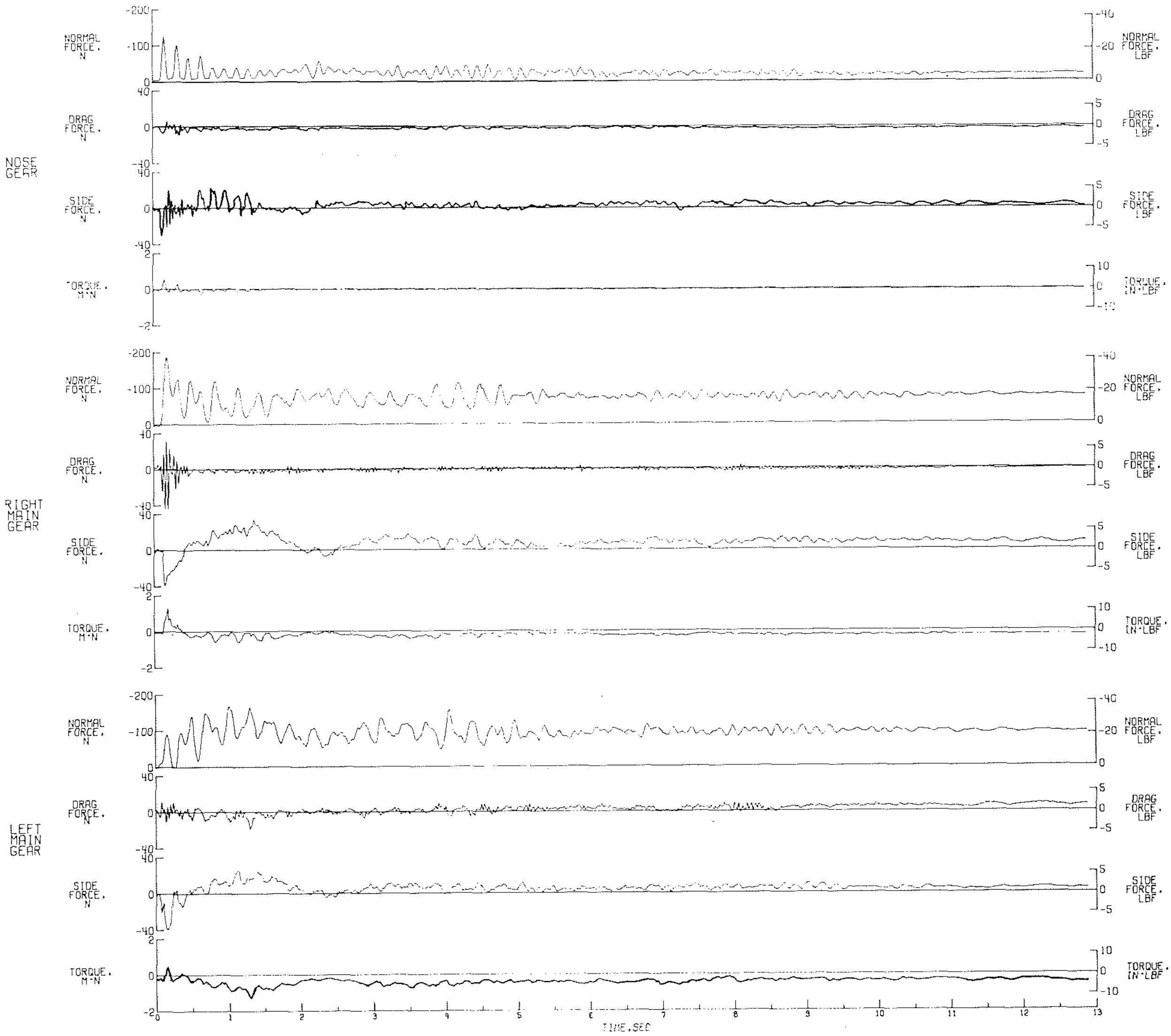
(a) Gear forces.

Figure 21.- Time histories of case 5 (concept D).



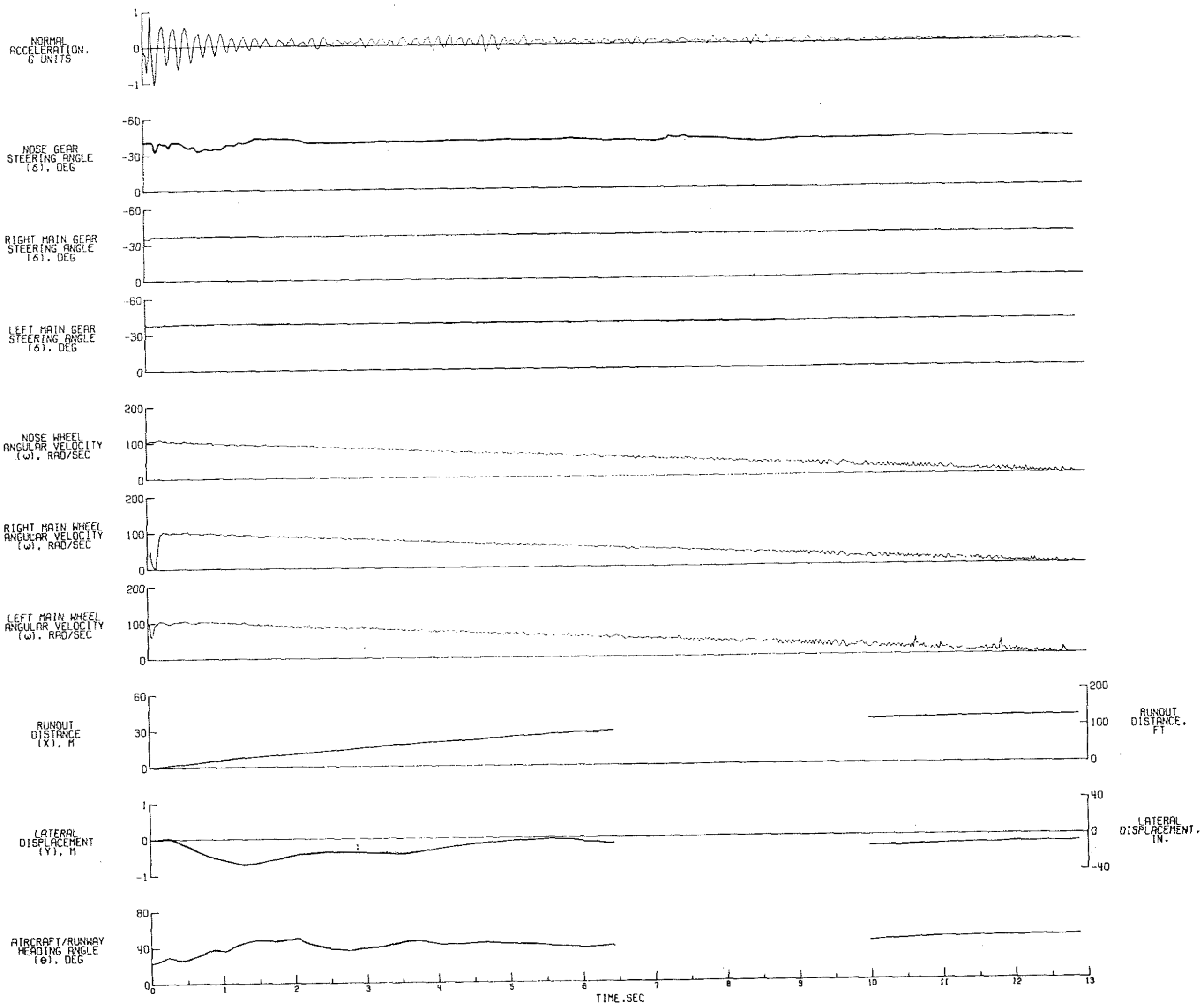
(b) Gear steering angles, wheel speeds, and vehicle-trajectory parameters.

Figure 21.- Concluded.



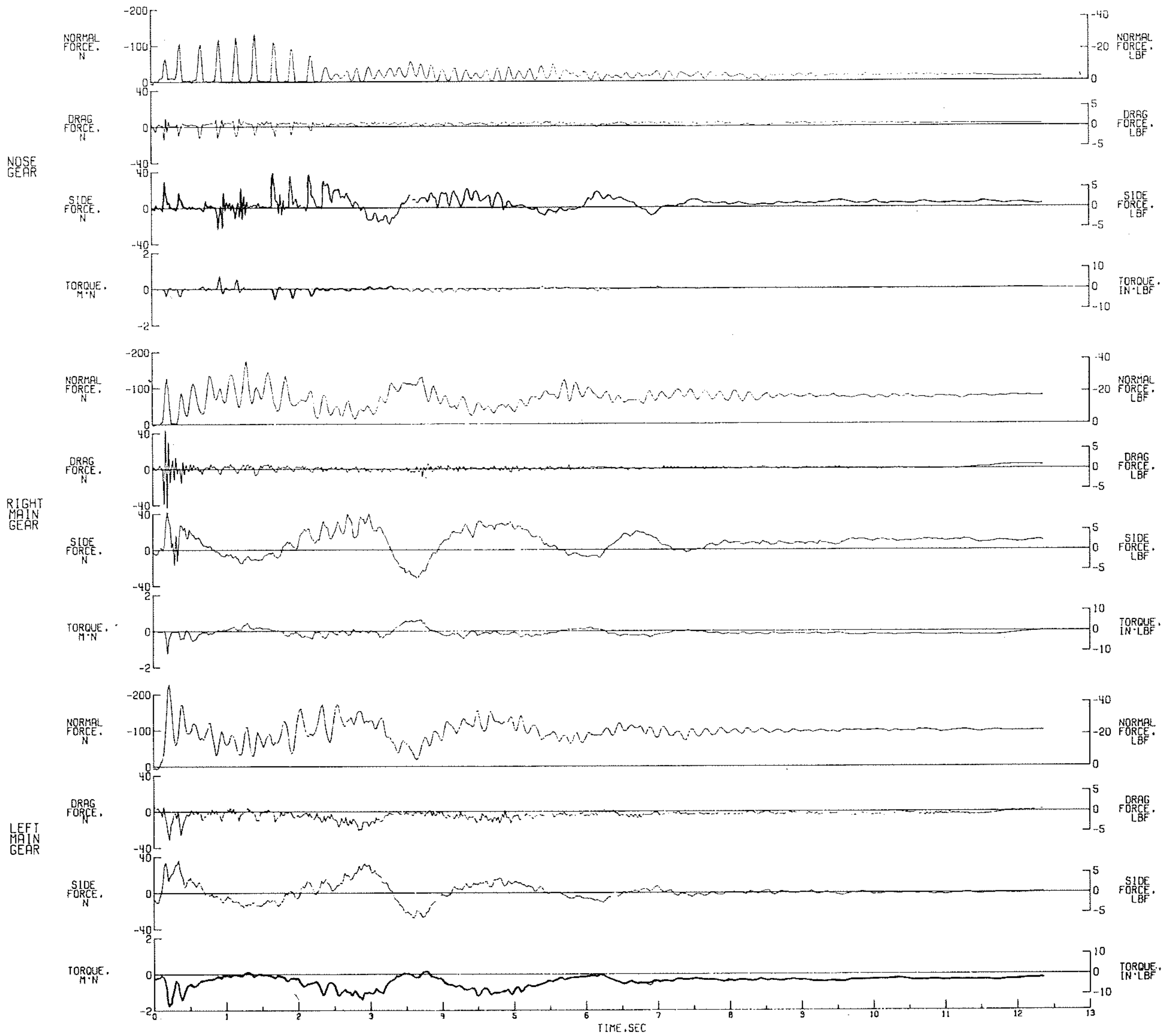
(a) Gear forces.

Figure 22.- Time histories of case 6 (concept D).



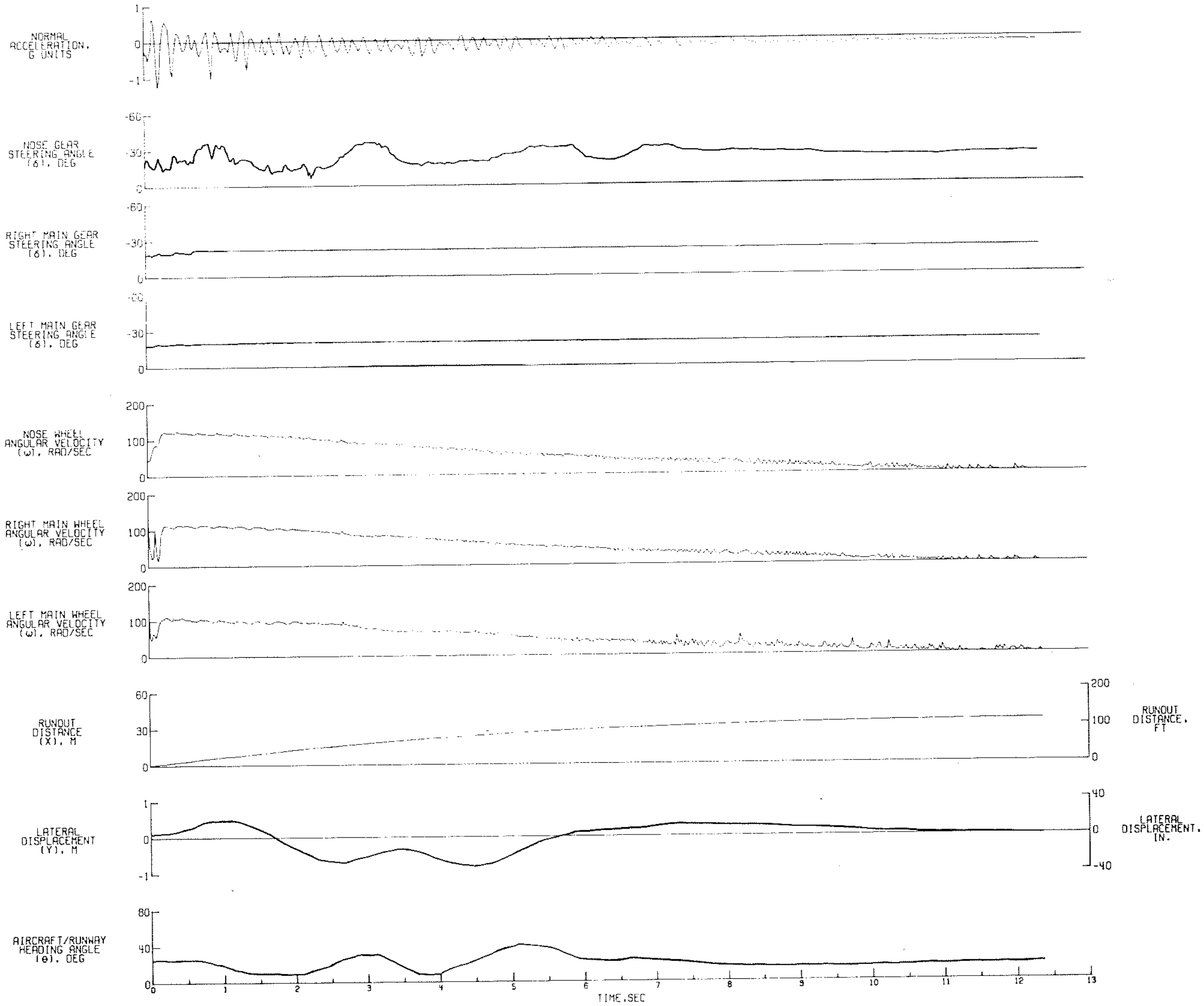
(b) Gear steering angles, wheel speeds, and vehicle-trajectory parameters.

Figure 22.- Concluded.



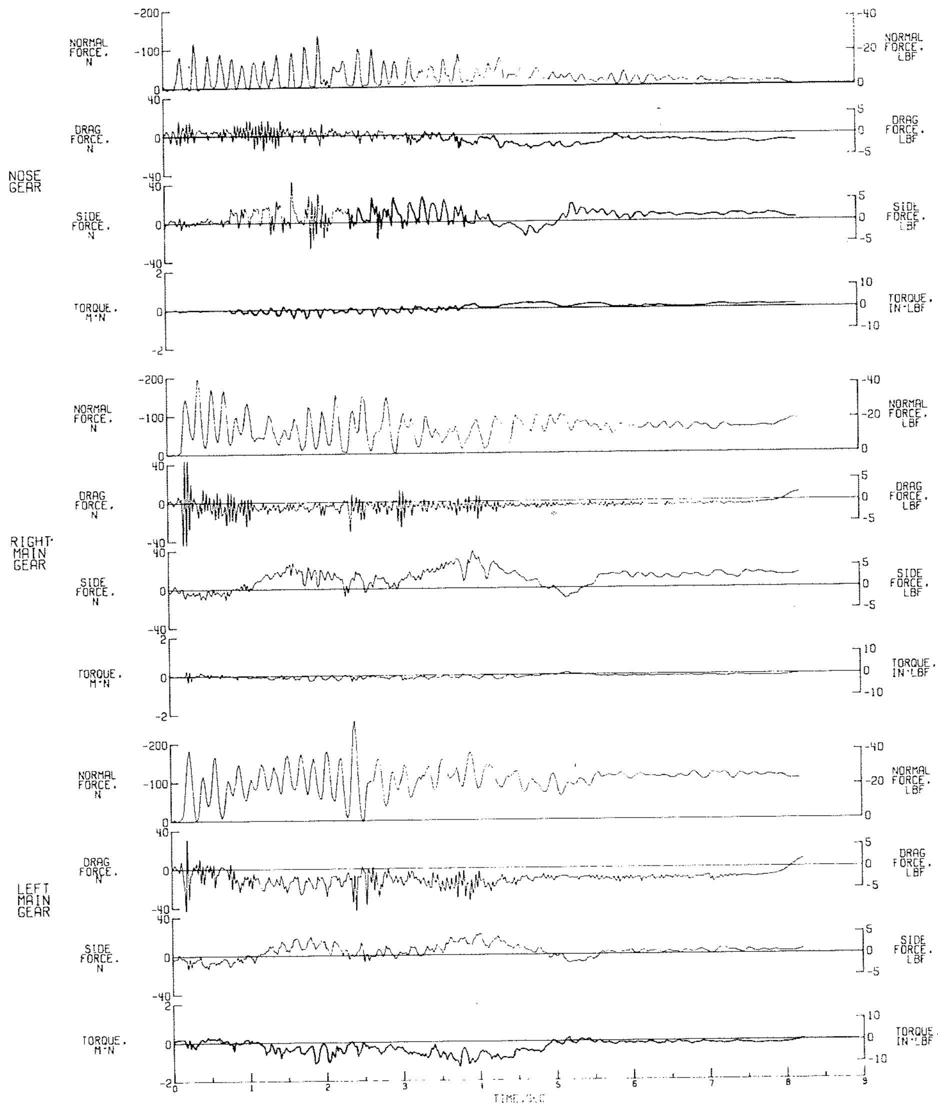
(a) Gear forces.

Figure 23.- Time histories of case 7 (concept D).



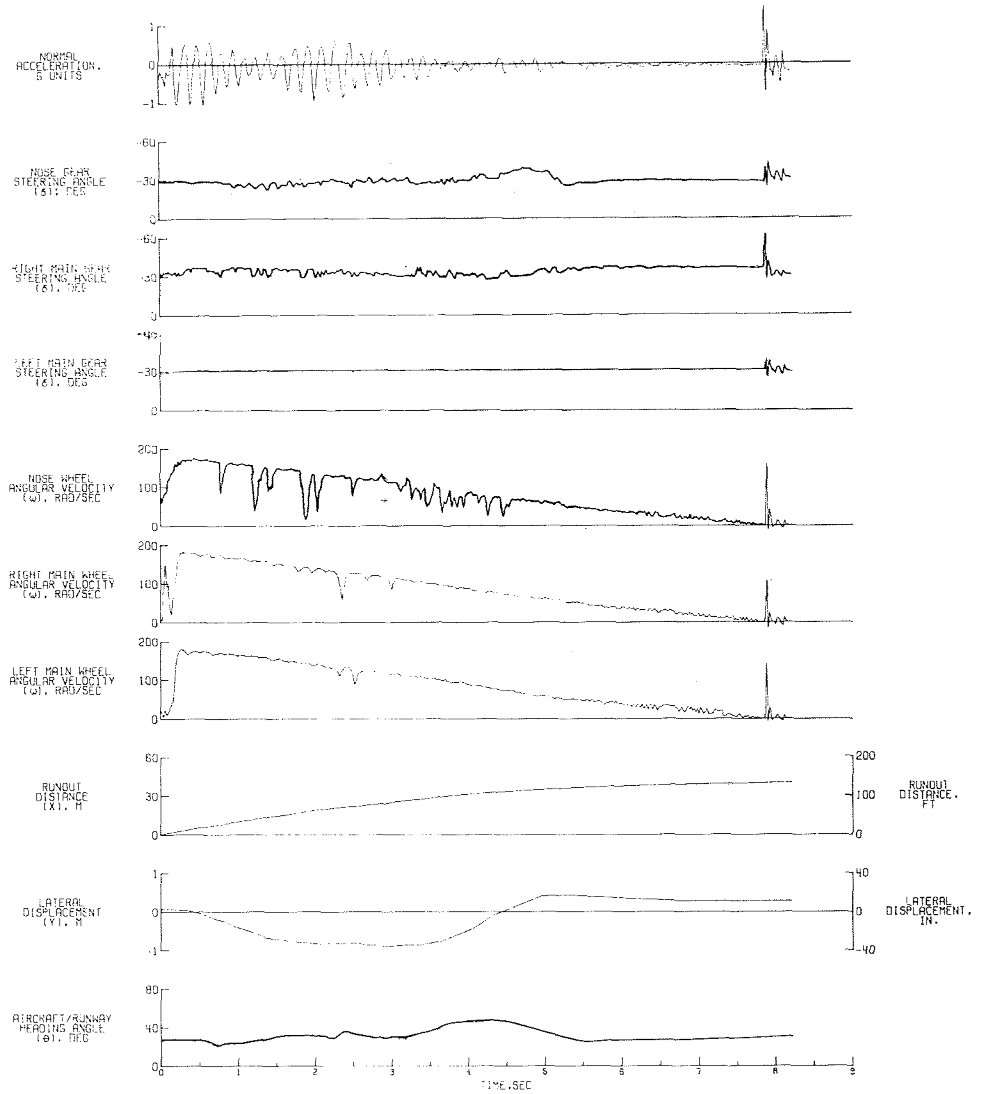
(b) Gear steering angles, wheel speeds, and vehicle-trajectory parameters.

Figure 23.- Concluded.



(a) Gear forces.

Figure 24.- Time histories of case 8 (concept D).



(b) Gear steering angles, wheel speeds, and vehicle-trajectory parameters.

Figure 24.- Concluded.

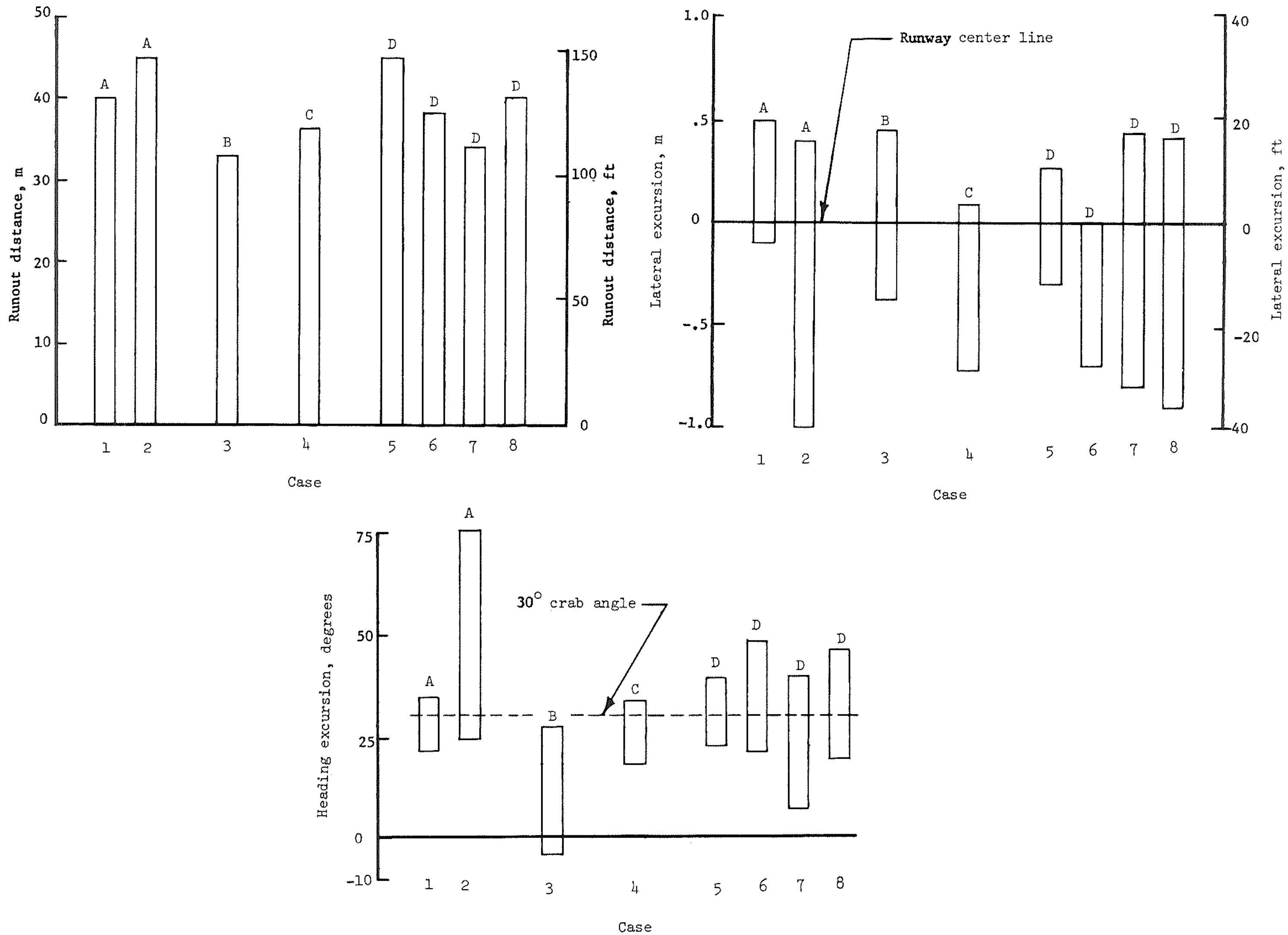


Figure 25.- Model lateral and longitudinal displacements and heading. Letters above the graphs denote the concept.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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