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RESEARCH MEMORANDUM

INVESTIGATION OF THE DYNAMIC LONGITUDINAL STABILITY OF TWO EQUAL-SIZE MODELS COUPLED IN TANDEM WITH A SINGLE JOINT

PRELIMINARY MODEL FLIGHT TESTS

By Robert E. Shanks and David C. Grana

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

An investigation is being made in the Langley free-flight tunnel to study the dynamic longitudinal stability of equal-size models coupled in tandem with a single joint which provides freedom in pitch between the models. This paper presents the results of some preliminary flight tests in which the joint was approximately equidistant from the centers of gravity of the two models and the models had a mechanical linkage which moved the elevator of the rear model so as to produce pitching moments tending to oppose relative displacement in pitch of the two models. All the flight tests were made for conditions which would have been statically stable if the combinations were rigid.

The flight tests showed that the behavior of the models was satisfactory in some conditions and that the stability of the combination was decreased as the elevator gearing ratio (ratio of elevator deflection to relative pitch angle) was decreased, as the ratio of the weight of the rear model to that of the front model was increased, or as the center of gravity of the front model was moved rearward.

INTRODUCTION

An investigation is being conducted in the Langley free-flight tunnel to determine the dynamic longitudinal stability characteristics of two models of equal size coupled together in tandem with a single joint. This arrangement would facilitate in-flight refueling by

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eliminating formation flying after coupling has been effected, if the combination is completely stable, and by simplifying the fuel transfer apparatus and technique. The results of a preliminary part of this investigation are reported herein.

This part of the investigation consisted of flight tests in which three geometric and mass parameters were studied. For all the tests the joint was about equidistant from the centers of gravity of the two models and the models had a mechanical linkage which could move the elevator of the rear model so as to produce pitching moments tending to oppose relative displacement in pitch of the models. The three parameters which were varied in the tests were: (1) the elevator gearing ratio (ratio of elevator deflection to relative pitch angle); (2) the weight ratio (ratio of the weight of the rear model to the weight of the front model) for the case of zero elevator gearing ratio; and (3) the location of the center of gravity of the front model for the case of 3:1 elevator gearing ratio.

SYMBOLS

S wing area (of one model), square feet

W weight of model, pounds

α angle of attack of longitudinal body axis, degrees

q dynamic pressure, pounds per square foot

$\bar{c}$ mean aerodynamic chord, feet

C_m pitching-moment coefficient (Pitching moment/$qS\bar{c}$)

C_L lift coefficient (Lift/qS)

C_D drag coefficient (Drag/qS)

I_Y moment of inertia of model about the lateral body axis, pound-feet^2

Subscripts:

1 front model

2 rear model

cg center of gravity

APPARATUS AND TESTS

All the tests were made in the Langley free-flight tunnel, a complete description of which is given in reference 1. The force tests were made on the free-flight-tunnel six-component balance which is described in reference 2.

A sketch of the two models used in these tests is presented in figure 1. The models were coupled together by a hinge which permitted freedom in pitch only. The wings were the same for each model and the horizontal tail surfaces were the same for each model; the wings and tails were located in the same relative positions. The boom of the rear model was longer than that of the front model in order that the distance from the joint to the center of gravity of each model would be the same when the center of gravity of each model was at 0.25 mean aerodynamic chord. Each wing had an aspect ratio of 6, a taper ratio of 0.43, and a Rhode St. Genese 35 airfoil section. The front model did not have a vertical tail because it would have been located so close to the center of gravity of the combination that it would have produced negligible stabilizing moments. The weights and pitching moments of inertia of the models for the various test configurations are given in table I.

The elevator of the front model was deflected by an electromagnetic mechanism which was operated by the pilot in the manner described in reference 1. The elevator of the rear model was operated by a simple mechanical linkage so that the elevator moved in proportion to the relative pitch angles of the models. The operation of this linkage is shown schematically in figure 2. The purpose of this linkage was to produce an aerodynamic moment tending to prevent change in the relative angle of pitch between the models; for example, as the angle of pitch of the rear model with respect to the front model increased positively, the rear elevator deflected downward and a moment was produced which tended to return the models to their trim alinement. The gearing ratio (ratio of the elevator deflection to the change in pitch angle between the models) could be varied in flight from about 3.5:1 to 0. For zero gearing, of course, there was no restraint between the models because the rear elevator did not respond to a change in angular alinement of the models.

The models were controlled laterally with the ailerons of the front model which were operated by an autopilot which was sensitive to displacements in bank, yaw, and lateral position. This autopilot kept the models flying in the center of the tunnel without manual lateral control by the pilot. The reference for the autopilot was provided by a fine wire running over a pulley near the top and front of the test section. One end of this wire was attached to a hinged pick-off arm on the autopilot. A small weight was attached to the other end of the wire to provide a light tension force in the wire. Because of this tension force the autopilot pick-off arm tended to remain alined with the reference wire when the model was displaced in bank, yaw, or lateral position. The autopilot case, of course, moved with the model so that a relative angular displacement was produced between the case and the arm. This relative displacement was used to control the proportional pneumatic servomechanism which actuated the ailerons. Although this system actuated the ailerons of the front model only, both models were stabilized laterally because the coupling was rigid in roll and yaw.

A complete list of the flight test conditions is given in table I. The models were tested through a range of elevator gearing ratios from 3.5 to 0, through a range of weight ratios (ratio of the weight of the rear model to the weight of the front model) from 0.63 to 0.71, and through a range of center-of-gravity positions of the front model from 0 to 0.13 mean aerodynamic chord. All the flight tests were made at a lift coefficient of approximately 1.0 based on the sum of the wing areas of the two models.

Force tests were made of the front model alone and of the two models coupled rigidly in tandem to determine the lift, drag, and pitching-moment characteristics of the individual models and of the combination. These tests were made at a dynamic pressure of 3.0 pounds per square foot; this pressure corresponded closely to the conditions of the flight tests.

RESULTS OF FORCE TESTS MADE TO DETERMINE THE AERODYNAMIC CHARACTERISTICS OF THE FLIGHT-TEST MODELS

The results of the force tests are given in figure 3. The coefficients for the combination were based on the sum of the wing areas of the two models and the mean aerodynamic chord of one wing, and the pitching-moment coefficients of the combination were referred to the joint. The coefficients of the single model were based on the wing area and mean aerodynamic chord of one wing, and the pitching-moment coefficients were referred to the quarter-chord point of the mean aerodynamic chord. The test results show that the single model was statically stable over the entire lift-coefficient range. The rigidly coupled combination was statically unstable at low and moderate lift coefficients but was stable at lift coefficients greater than about 0.75. This change in the slope of the pitching-moment curve is believed to have resulted principally from the effects of changes in the downwash of the front model on the rear model, but the exact nature of these effects has not yet been fully investigated. For all the flight test conditions the lift coefficient was about 1.0 and the center of gravity of the combination was located forward of the joint. The force-test results show that the flight tests were made in conditions for which the models would have been statically stable if they had been rigidly coupled.

FLIGHT TEST RESULTS AND DISCUSSION

Characteristics of Model Motions

The flight behavior of the models was determined by visual observation and from motion-picture records. Usually the only apparent mode of the longitudinal motion was a relatively long-period oscillation which consisted primarily of vertical motion and pitching of the combination with some slight pitching of one model relative to the other. At times, a heavily damped short-period oscillation was also evident. This oscillation consisted primarily of relative pitching of the two models. Unlike a phugoid oscillation in which there is essentially no change in angle of attack, the long-period oscillation was characterized by a definite increase in angle of attack as the combination moved downward, and a decrease in angle of attack as the combination moved upward. The period of oscillation was about 2 seconds. A summary of the longitudinal stability characteristics for all the test conditions is presented in table I. These results are for the long-period motion only because the short-period oscillation was always heavily damped. The motions which were described as "neutrally stable oscillations" were constant-amplitude hunting oscillations which showed no tendency to damp or to build up over long periods of time. For conditions in which these hunting oscillations were encountered, the oscillation usually was unstable for small amplitudes, and the amplitude increased until some nonlinear force or moment variation prevented it from increasing farther. In most of the unstable conditions the pilot was not able to control the models successfully. Because the period will be longer (about 15 sec) for corresponding full-scale airplanes of existing transport or bomber size, the airplanes could probably be controlled in some of these unstable conditions.

Effect of Elevator Gearing Ratio

A systematic reduction of the gearing ratio was made for the configuration in which the centers of gravity of the front and rear models were located at 0 and 0.25 mean aerodynamic chord, respectively, and the weight ratio was 0.83. (See table I.) As the gearing ratio was reduced from 3.5:1 to about 0.25:1 there was a gradual decrease in stability. At the highest gearing ratio the longitudinal oscillation was well-damped and the model flew steadily, but at the lowest gearing ratio the model was easily disturbed and the oscillation was unstable. Even though the oscillation was unstable, the pilot was able to control the motion in this case.

The uncontrolled model motion shown in figure 4 illustrates the effect of change in gearing ratio. During the flight the gearing ratio was reduced from 3:1 to 0 for a condition in which the center of gravity of the front model was at 0.18 mean aerodynamic chord and that of the rear model was at 0.36 mean aerodynamic chord. With the 3:1 gearing ratio the motions consisted of a constant-amplitude oscillation which indicated about neutral stability. When the gearing ratio was reduced to 0, the combination became very unstable. Examination of the motion shown in figure 4 indicates that just as the gearing ratio was reduced from 3:1 to 0, the model was inadvertently disturbed in such a way that the oscillation was stopped. The model continued to fly smoothly for about 2 seconds before receiving another disturbance which initiated the unstable oscillation.

Effect of Weight Ratio

The effect of increasing the weight ratio was determined for conditions in which the center of gravity of both models was at 0.25 mean aerodynamic chord and the elevator gearing ratio was 0. The results presented in table I show that for the lower weight ratios the longitudinal motions of the combination were stable, but that the stability decreased as the weight ratio was increased; in fact, at the highest weight ratio (0.71), the combination was unstable. The actual vertical motions for weight ratios of 0.68 and 0.71 are compared in figure 5. This figure clearly shows the light damping of the oscillation at the weight ratio of 0.68 and the instability of the oscillation at the weight ratio of 0.71.

Effect of Static Stability of the Front Model

The effect on dynamic stability of changing the static stability of the front model for the case where the elevator gearing ratio is 3:1 is given in table I. For this investigation the weight ratio was 0.93 and the center of gravity of the rear model was at 0.25 mean aerodynamic chord. Although the variations in the static stability of the front model were accompanied by small changes in the values of the pitching moment of inertia, these changes are believed to be insignificant. The stability of the combination decreased as the center of gravity of the front model was moved back in progressive steps from the leading edge of the mean aerodynamic chord to 0.13 mean aerodynamic chord. For the 0.13-mean-aerodynamic-chord center-of-gravity configuration the longitudinal oscillation was neutrally stable.

The decrease in dynamic stability of the combination with decrease in static stability of the front model might be explained as follows: As the gearing ratio increases, the restraint between the models increases so that the combination would effectively be rigidly coupled if the gearing ratio were infinite. The gearing ratio used in these tests (3:1) provided a relatively high degree of restraint so the behavior of the test configuration might be expected to be similar to that of a rigidly coupled configuration. Since, for a rigid configuration, rearward movement of the center of gravity reduces the stability, a reduction in stability should also be expected for the test configuration with 3:1 elevator gearing ratio when the center of gravity of the front model (and hence the center of gravity of the combination) was moved rearward.

CONCLUDING REMARKS

The results of tests made in the Langley free-flight tunnel to determine the effect of three parameters on the dynamic longitudinal stability of two models of equal size coupled together in tandem with a single joint which was approximately equidistant from the centers of gravity of the two models can be summarized as follows: The behavior of the models was satisfactory in some conditions and the stability of the combination was decreased as the elevator gearing ratio (ratio of elevator deflection to relative pitch angle) was decreased, as the ratio of the weight of the rear model to that of the front model was increased, or as the center of gravity of the front model was moved rearward. These test results were obtained for conditions which would have been statically stable if the combinations were rigid. Some preliminary theoretical studies have indicated that these parameters would not necessarily have had the same effects if the tests had been made for conditions which were statically unstable for a rigid combination. Although the model oscillations were uncontrollable in many of the unstable conditions because of the rather short period, the period of the oscillation for full-scale airplanes might be long enough to enable the pilot to control this motion.

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REFERENCES

1. Shortal, Joseph A., and Osterhout, Clayton J.: Preliminary Stability and Control Tests in the NACA Free-Flight Wind Tunnel and Correlation with Full-Scale Flight Tests. NACA TN 810, 1941.

2. Shortal, Joseph A., and Draper, John W.: Free-Flight-Tunnel Investigation of the Effect of the Fuselage Length and the Aspect Ratio and Size of the Vertical Tail on Lateral Stability and Control. NACA ARR 3D17, 1943.

TABLE I

SUMMARY OF FLIGHT TEST RESULTS

Purpose of tests	Weight of front model (lb)	Weight ratio, W_2/W_1	Moment of inertia, I_Y (lb-in.^{2})		Center-of-gravity location (percent $\bar{c}$)		Elevator gearing ratio	Longitudinal stability
			Front model	Rear model	Front model	Rear model		
Effect of elevator gearing ratio	3.29	0.83	271	262	0	25	3.5:1	Stable oscillation
	3.29	.83	271	262	0	25	1.5:1	Stable oscillation
	3.29	.83	271	262	0	25	1.0:1	Neutrally stable oscillation
	3.29	.83	271	262	0	25	.50:1	Neutrally stable oscillation
	3.29	.83	271	262	0	25	.25:1	Unstable oscillation
	3.23	.93	255	294	13	36	3:1	Neutrally stable oscillation
	3.23	.93	255	294	13	36	0	Unstable oscillation
Effect of weight ratio	4.05	.63	239	262	25	25	0	Stable oscillation
	3.83	.68	239	262	25	25	0	Stable oscillation, but light damping
	3.61	.71	239	262	25	25	0	Unstable oscillation
Effect of static stability of front model	3.29	.93	271	262	0	25	3:1	Stable oscillation
	3.29	.93	266	262	4	25	3:1	Stable oscillation
	3.29	.93	260	262	8	25	3:1	Stable oscillation, but light damping
	3.29	.93	255	262	13	25	3:1	Neutrally stable oscillation

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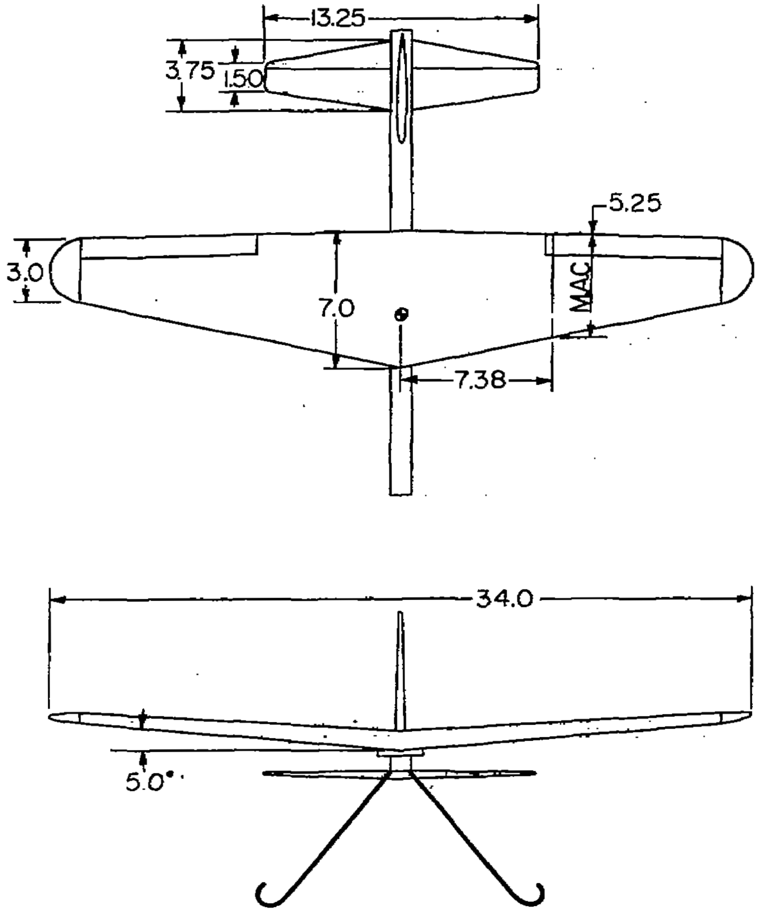
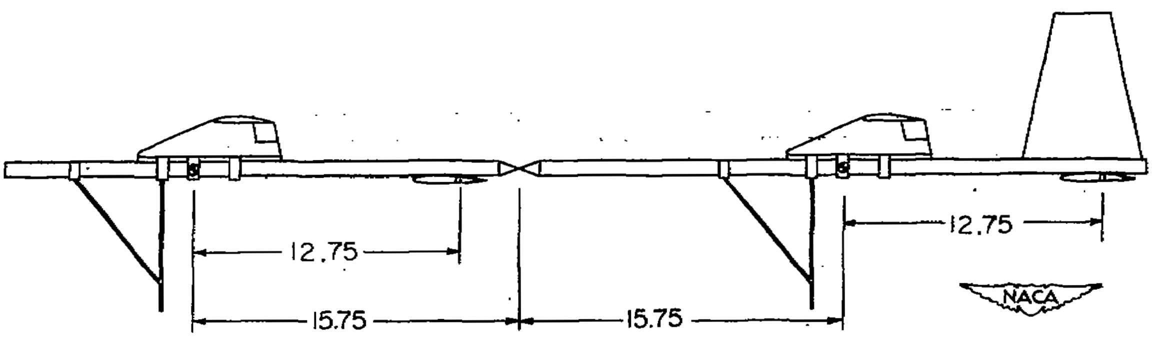


(a) General dimensions of a single model.



(b) General arrangement for the tandem-coupled configuration.

Figure 1.- Three-view sketch of the models used in the tests. All dimensions are in inches.

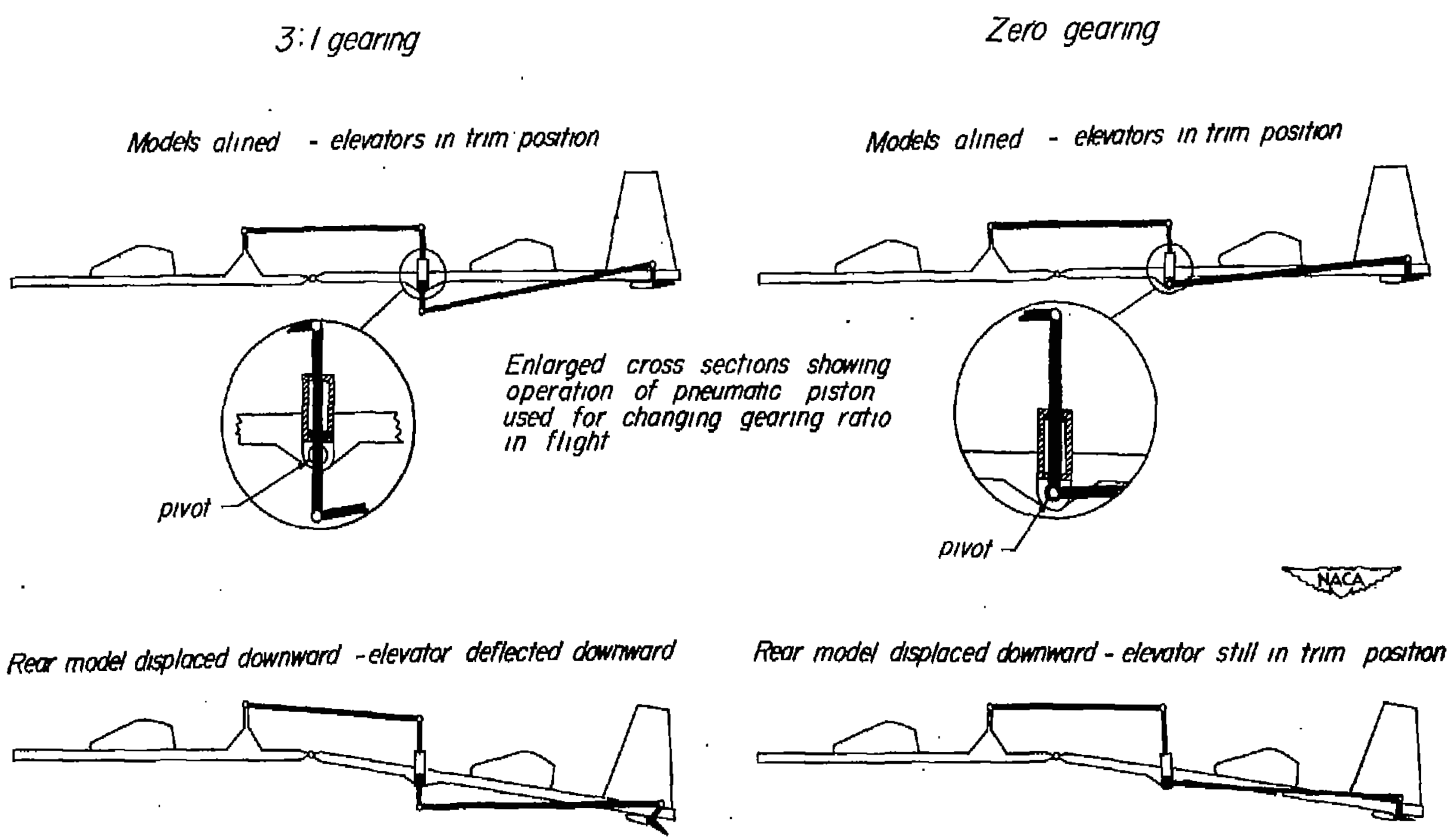


Figure 2.- Schematic diagram illustrating the operation of the elevator linkage.

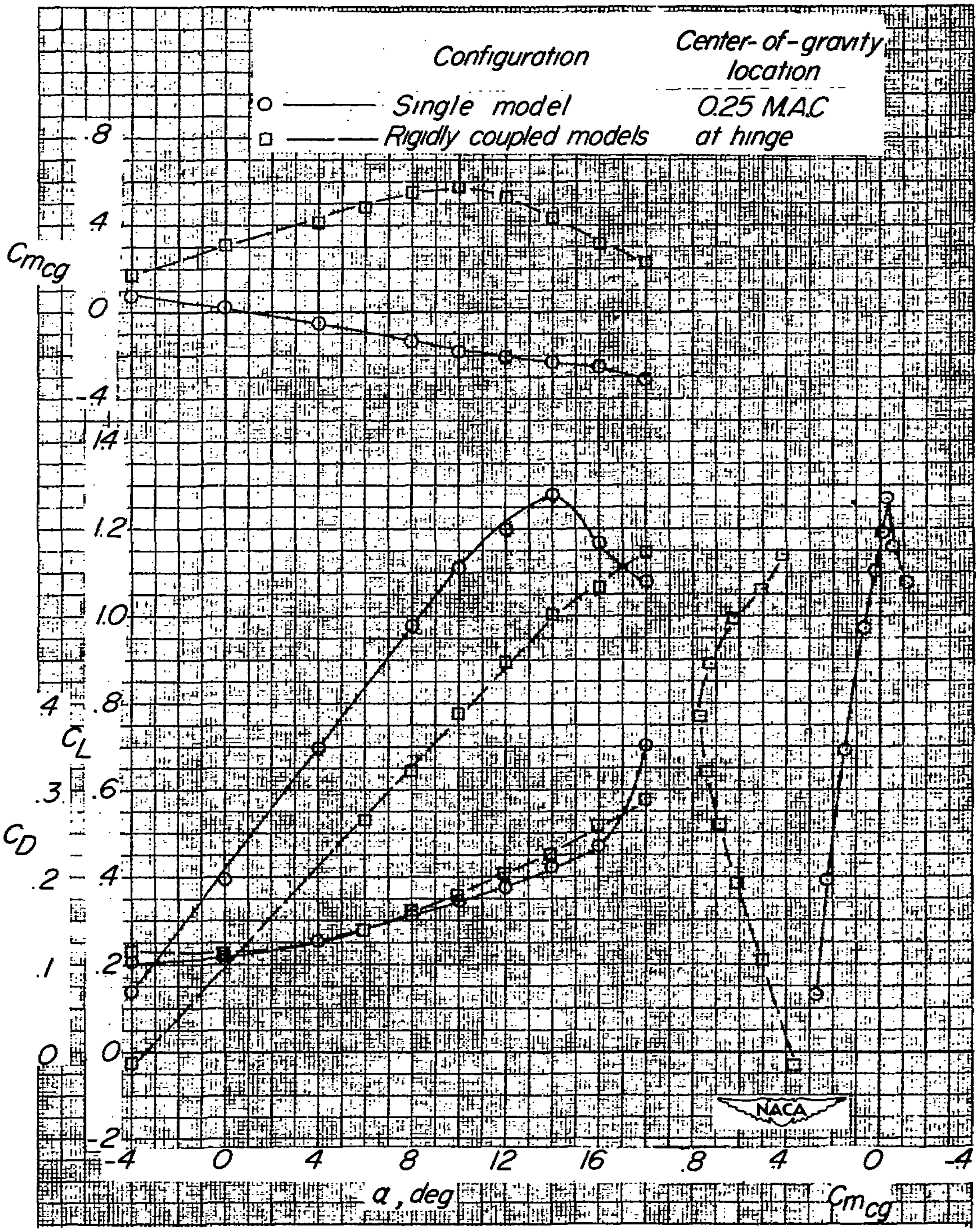


Figure 3.- Lift, drag, and pitching-moment characteristics of a single model and of the two models coupled rigidly in tandem. Tail incidence of single model was 0°; tail incidence of coupled models was: front, -5°; rear, -10°.

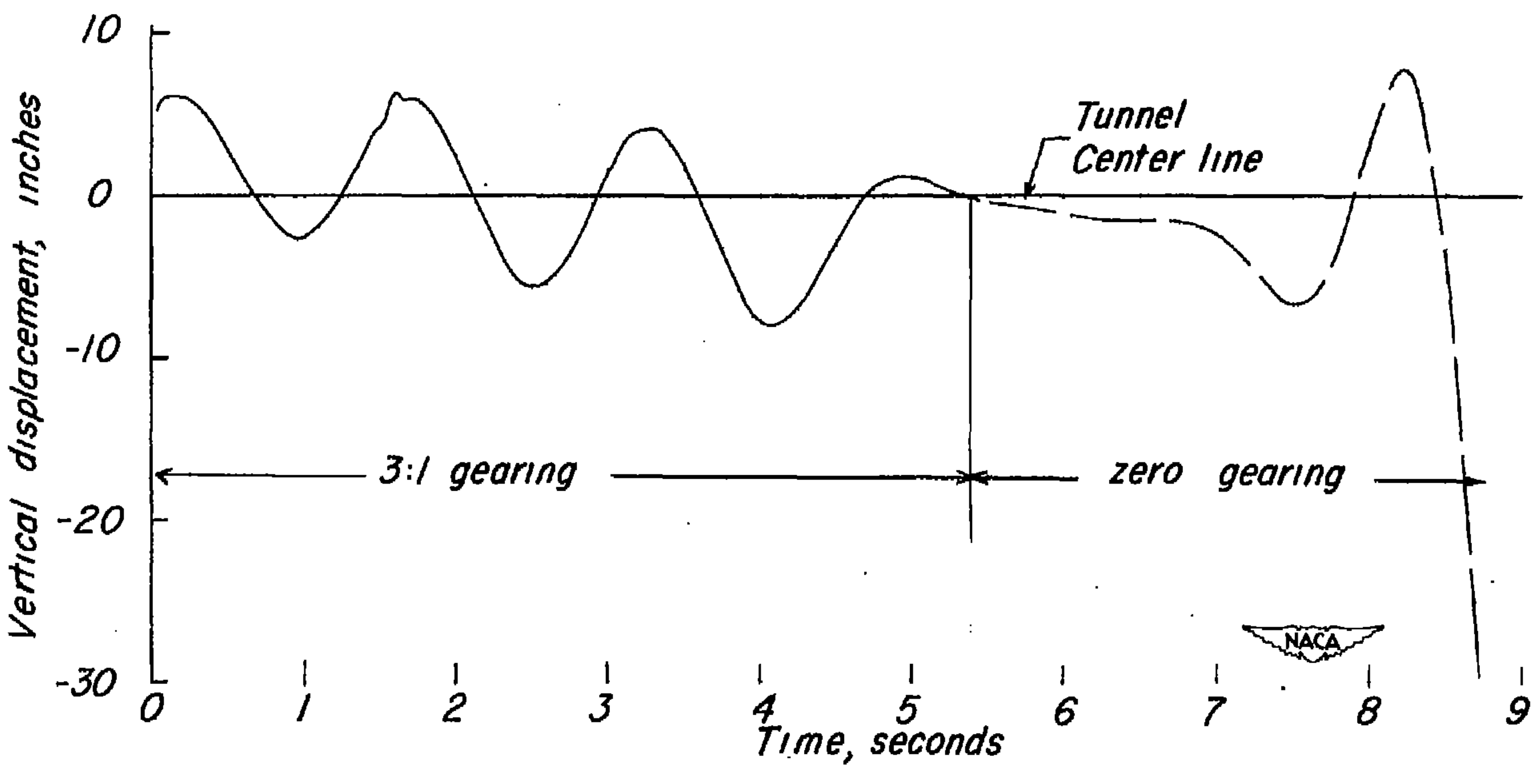


Figure 4.- Comparison of model motions for elevator gearing ratios of 3:1 and 0. Weight ratio 0.93; center of gravity of front model at 0.18 mean aerodynamic chord; center of gravity of rear model at 0.36 mean aerodynamic chord.

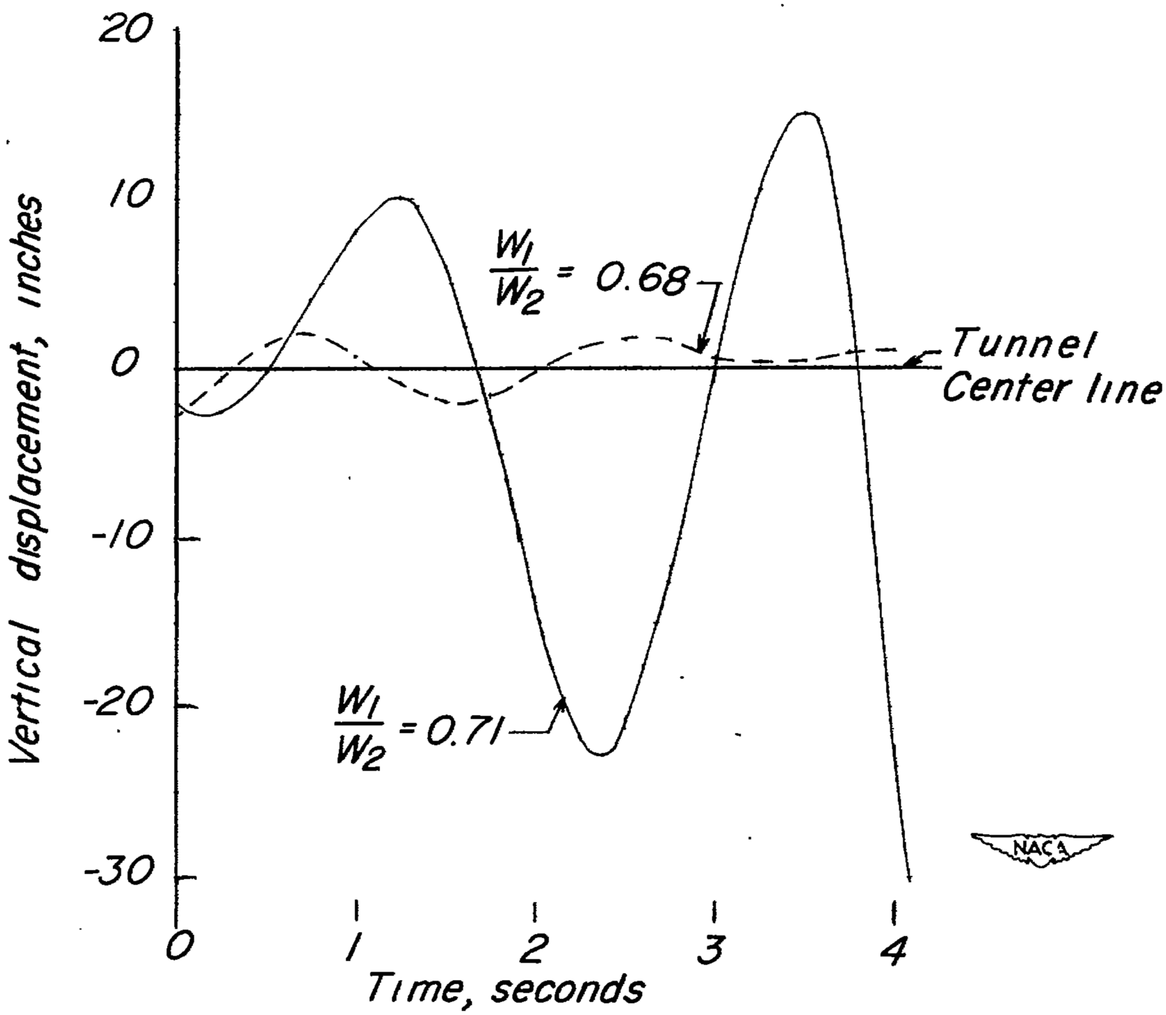


Figure 5.- Comparison of model motions for weight ratios of 0.68 and 0.71. Center of gravity of each model at 0.25 mean aerodynamic chord.

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