Test Techniques Used by NASA for Investigating Dynamic Stability Characteristics of V/STOL Models

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The three techniques covered in the paper are 1) the free-flight technique for studies of the motions of remotely controlled models with complete freedom, 2) the control-line technique for studies of the longitudinal motions of laterally restrained models, and 3) the forced-oscillation method for quantitative determination of the dynamic stability derivatives. The test techniques and hardware used in the tests are described, but the emphasis is placed on the use of the various techniques, with illustrations of the types of results that have been obtained. The two flight techniques are particularly valuable in providing an over-all view of the basic characteristics of a configuration. The test results are usually qualitative, but very often they outline quickly the areas of satisfactory behavior as well as areas in which further research is needed to produce acceptable flight behavior. In cases where some improvement in flight behavior is required, the changes can be made very quickly and cheaply at model scale, and the effects of the changes can then be evaluated rapidly by subsequent flight tests. Correlation between model tests and experience with full-scale aircraft has proven to be very good, as long as proper consideration is given to Reynolds number effects. The forced-oscillation tests are made to provide dynamic stability derivatives for theoretical analyses and simulator studies.

Introduction

THE unusual combination of requirements which a V/STOL aircraft must meet has led to many highly unconventional configurations. The dynamic stability characteristics of these configurations have been very difficult or impossible to predict on the basis of past experience with conventional airplanes. This paper will discuss three model test techniques used by NASA in investigating the dynamic stability characteristics of V/STOL aircraft. These techniques are the free-flight technique, the control-line technique, and the forced-oscillation technique. In the free-flight and control-line techniques, the motions of powered dynamically scaled models are the test data. A properly scaled model in flight may be thought of as being an analog computer combining the correct aerodynamic and mass inputs in the correct relationship to produce, as output, motions closely corresponding to those of the full-scale airplane. It is recognized that flying models may not yield exact quantitative results but do provide avenues of qualitative evaluation. In the forced-oscillation technique, the aerodynamic forces and moments acting on a model are the output and are used to evaluate numerically some of the more important stability derivatives necessary to computer or simulator studies. The techniques themselves and the test equipment and model hardware have been described in considerable detail in Refs. 1–3. The emphasis of the present paper is primarily on the use of the techniques and the type of results that can be obtained.

Flight-Test Techniques

Free Flight

Discussion of technique

In the free-flight technique, illustrated in Fig. 1, the model is flown without restraint in the 30- by 60-ft open-throat test section of the Langley full-scale tunnel, remotely controlled about all three axes by human pilots. The pilots who control the model about its roll and yaw axes are located in an enclosure at the rear of the test section where they can best view the lateral motions of the model. The pitch pilot, model power operator, and safety cable operator are stationed on a balcony at the side of the test section. Pneumatic and electric power and control signals are supplied to the model through the flexible trailing cable, which is made up of wires and light plastic tubes. This trailing cable also incorporates a $\frac{1}{8}$-in. steel cable that passes through a pulley above the test chamber. This cable is used as a safety cable to catch the model in case it goes out of control during a flight. The the open-throat test section is a very important feature of the tunnel free-flight model tests because it permits the model to swing out of the test section without being damaged following wild motions that would result in its being destroyed against the walls in a closed section.

One shortcoming of the tunnel for model flight testing is that the speed cannot be changed very rapidly. Thus, for VTOL model tests in the transition from hovering to cruising flight, only very gradual transitions can be simulated. For example, it usually requires about a minute to make the transition from hovering to conventional forward flight at a model flight speed of about 50 knots.

Normally, the flight tests represent level flight transitions, but the technique has been extended to permit tests for other conditions such as descending flight, which has proved particularly troublesome in some V/STOL configurations. The factors involved in the simulation of a descent condition are illustrated in Fig. 2. On the left-hand side of the figure is shown the balance of forces for a descent condition. For a descent condition, the airplane must have a net aerodynamic drag, and the lift, drag, and weight forces are in balance, with the drag being balanced by the forward component of the weight acting along the flight path. For the simulated descent condition in level flight, the model is flown with effectively the same lift and drag, but the drag cannot be balanced by a component of the weight and must be balanced by some thrust force, as indicated in the right-hand side of Fig. 2, which is independent of the normal airplane lift and propulsion system. This has been accomplished with a small high-pressure compressed-air jet exhausting from the rear of the model where the aerodynamic interference effects would be

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negligible. In this way the aerodynamic effects of descending or decelerating flight, which are very important for many V/STOL types, can be simulated with the model in level flight in the tunnel. This method of simulation, however, does not account for the effects of descent angle on classic dynamic lateral stability, but fortunately these effects are small for the descent angles likely to be encountered in normal operation and are of much less importance than the aerodynamic effects that can be correctly simulated.

For hovering tests where there is no requirement for airspeed, the same technique and setup are used except that the tunnel test section is not needed. The model is then set up in a hovering test area located in a large enclosure where the pilots can be stationed closer to the model than is possible in the test section. It has been found very desirable, particularly during tests in which the model is flown very close to the ground, for the pilots to be near the model so that they can notice more readily, and correct for, slight changes in model attitude and altitude.

This model flight technique, in which the piloting duties are divided among several men, is used in preference to the conventional single-pilot technique to offset three fundamental differences between model and full-scale flight conditions which make the model more difficult to fly. The first of these is that the model must be flown within the confines of the test section, which prohibits the model pilot from allowing the development of certain mild drifting motions or slight changes in speed which would be of little concern to the pilot of a full-scale airplane operating in open air. A second factor is that the angular motions of a dynamic model are much more rapid than those of its full-scale counterpart, which gives the model pilot less time in which to apply a corrective control. The third factor is that the model pilot is remotely located, which makes it impossible for him to feel an acceleration as a full-scale pilot can. The lack of feel of the acceleration introduces considerable lag in the model pilot's application of control since he must, instead, rely on visual observations of some model displacement before he recognizes the need for corrective control. His control application is therefore slightly later in time and, because of the relative rapidity of the model's motion, even later in phase than the full-scale pilot's control. The effect of these factors is offset somewhat by the use of separate pilots for various phases of the model motions, so that each man has less to do and can concentrate on one particular phase of the motion. The model pilots are research engineers experienced in model flying. Full-scale piloting experience is not required because the three factors just discussed result in a piloting technique entirely different from that used in full-scale flying.

Use of the free-flight model technique

An important part of interpreting the model behavior, that is, in making allowances for the foregoing factors, is long experience in flying models for which full-scale aircraft experience is available for correlation. A background knowledge of what type of model behavior represents satisfactory or unsatisfactory aircraft behavior is, of course, required. As a result of these factors, the flying model technique has a special field of application. The models should be used to get a qualitative indication of the dynamic behavior of the aircraft and the relative ease of control and not as a quantitative indication of exactly what would happen and under exactly what conditions. During the past 20 years, this technique has been applied in the early stages of research on many configurations that were novel at the time, e.g., tailless configurations, canards, highly swept and delta wings, coupled aircraft, and, more recently, V/STOL aircraft and spacecraft entry configurations. Experience has shown it to be a useful tool in exploratory investigations on new types of aircraft where there was no background of experience to permit the calculation of the motions with any degree of certainty. This is particularly true in the V/STOL field, where new regimes of flight, large power effects, and stalled or near-stalled conditions have had to be considered. The technique has been used to point out many of the main stability and control problems of V/STOL configurations, some of the more important stability parameters, and cures for some of the troubles.

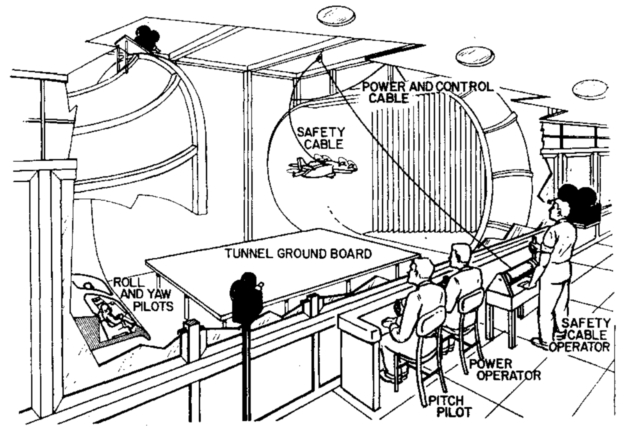

Fig. 1 Test setup for free-flight model testing in NASA Langley Research Center full-scale tunnel.

The stability, controllability, and the general flight behavior are determined qualitatively from the pilots' observations, and motion-picture records of the flight tests are made also as an aid in the pilots' evaluation. The general flight behavior is, in effect, much the same as the pilot's feel of an airplane or his qualitative opinion of the flying qualities and indicates whether stability and controllability are adequate and properly proportioned. If the behavior of a configuration proves to be unsatisfactory in any way, methods for achieving satisfactory characteristics can be studied by changes in piloting technique, by geometric changes to the model, or by the use of artificial stability augmentation. One of the greatest advantages of model testing is, of course, the relative ease, safety, and low cost of investigating gross changes in aircraft characteristics.

In hovering flight, the basic stability of the configuration is studied by having two of the pilots controlling the model as steadily as possible while the third pilot makes his test. In this manner the uncontrolled (stick-fixed) pitching or rolling motion of the model can be determined. An example of this type of motion, which is sometimes encountered, is shown in Fig. 3, which was reproduced from Ref. 4. The curves of Fi.g 3 show time histories comparing the stick-fixed rolling motions of ducted and unducted aerial jeep configurations in hovering flight. Angle of bank and lateral displacement are plotted against time with the model results scaled up to 3000-lb machines. In this case, both types had unstable oscillations with the ducted propeller configuration's motion being more rapidly divergent and of shorter period. Some V/STOL configurations, such as the jet types, usually exhibit simple divergences rather than oscillations.

Controllability is determined with the same setup by each pilot in turn varying his control power and determining how

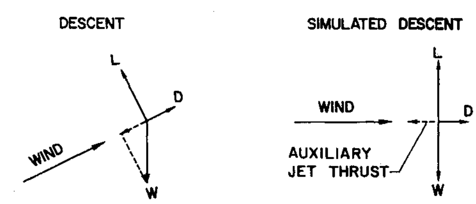

Fig. 2 Balance of forces in descent and simulated descent conditions.

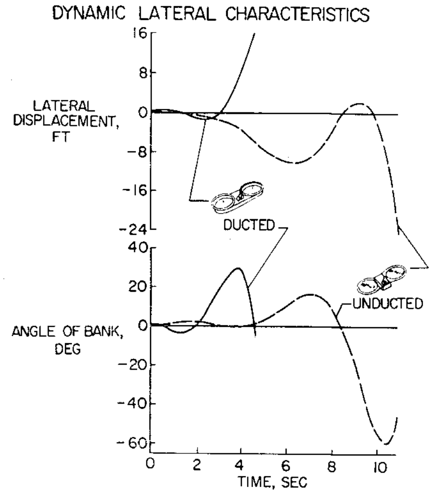

Fig. 3 Dynamic lateral characteristics.

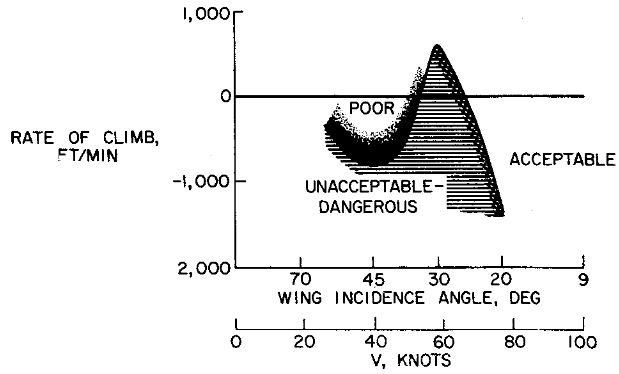

Fig. 5 Rate of descent limitations for VZ-2 with the basic wing.

much control is adequate for steady flying and for performing various maneuvers. In the beginning it was felt that an indication of control power required could not be obtained with this technique because of the remote pilot position and model size factors discussed earlier. Experience has shown, however, that the model pilots demand about the same maximum control powers in pitch and roll as has been found desirable in full-scale aircraft such as the V/STOL test beds. Yaw control has not shown this correlation with full-scale experience because the yaw control task in model flying is mainly one of simple alignment under steady flying conditions and does not involve gusts, cross winds, or other disturbances and requirements found in full-scale tests.

The basic stability or controllability of a model does not, however, give the complete picture, and this is where the model pilots' evaluation of the general flight behavior is important. For example, there have been cases where the basic stability of a model has been essentially the same in pitch and roll, but the flight behavior has been entirely different. A recent flight test of a fan-in-wing model showed longitudinal control to be extremely easy while roll control was very touchy. Flight-test records showed that the stick-fixed instability was actually about the same in either case. The flight tests indicated, however, that the model was much more sensitive to disturbances or translation in roll than in pitch and that it consequently had to be flown with close attention at all times. These results were taken to indicate that the longitudinal characteristics were satisfactory, but that artificial damping would probably be required in roll, at least in other than ideal conditions of operational use.

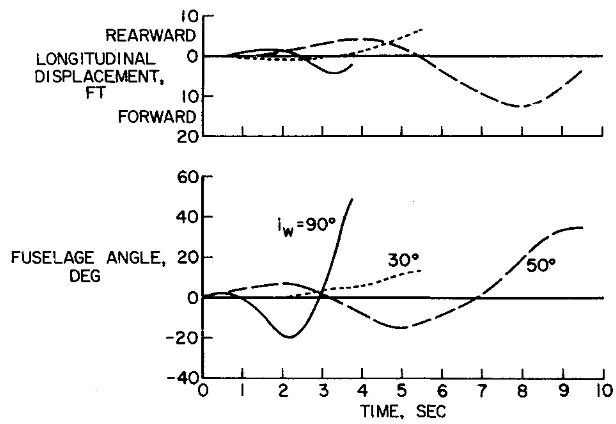

Fig. 4 Uncontrolled pitching motions of a tilt-wing model.

The characteristics of V/STOL configurations are also studied at takeoffs and landings and in hovering near the ground. The models are flown at various heights above the ground to study not only the well-known "ground cushion" effect on thrust required and on control power, but also the effect on general flight behavior of random disturbances caused by reflected or recirculated slipstreams. The basic stability of a model can also be changed near the ground. For example, flights of a $\frac{1}{8}$-scale model of the X-18 tilt-wing aircraft showed that the unstable pitching oscillation motion that was present in hovering out of ground effect became neutral as it approached the ground and actually became stable when the model was flown very close to the ground. The model would fly for relatively long periods of time at this height without the pitch pilot giving any corrective control.

Transition characteristics can be studied in the full-scale tunnel either by continually increasing the tunnel airspeed until the transition is completed or by holding the tunnel airspeed constant at intermediate speeds for more careful study of any stability and control characteristics or problems that may be encountered in the transition. Tests are made to determine control interaction, possible control mixing requirements, and whether control power is adequate for dealing with trim changes. Ways of minimizing trim changes, such as programed flaps or tail incidence changes, can be evaluated in addition to determining the effect of these changes on the dynamic stability characteristics.

The basic stability of the models during transition can be determined during the constant airspeed flight tests. An example of the type of motion studied during such tests is shown in Fig. 4. Time histories are shown of the stick-fixed pitching motions of a four-propeller tilt-wing research model of Ref. 5 for wing incidence angles representing three different airspeeds. The curves show that the stick-fixed motion in hovering was an unstable oscillation. As the forward speed increased, the motions became less unstable and the period of the oscillation became quite long. At 30° wing incidence, the motion was not oscillatory but simply diverged slowly, evidently because of some out-of-trim moment.

The free-flight technique is also useful in investigating the general flight behavior for conditions or problems that involve factors other than classic stability. For example, in some V/STOL configurations, the lifting surfaces are often operated in a near-stalled condition during transition, particularly for decelerating or descending flight. Past experience with the full-scale VZ-2 two-propeller tilt-wing research aircraft has shown that the reduced power conditions in descent flight result in wing stalling that leads to buffeting, abrupt wing dropping, and generally sloppy wallowing motions of the aircraft in one of the most critical regions of operation-landing approaches. The effect of this wing stalling on the handling qualities of the VZ-2 aircraft is usually illustrated, as in Fig. 5, on a plot of rate of climb vs airspeed which shows handling quality boundaries between acceptable and unacceptable characteristics. Furthermore, the correlation of flight experience and wind-tunnel tests at either small or large scale (static force tests or tuft tests) was not adequate to indicate that either the boundaries or the seriousness of the behavior could have been predicted from the wind-tunnel tests. A free-flight model investigation, however, gave a fairly good indication of the aircraft's descent capability, including the effect of flaps in greatly improving the capability, from an over-all handling qualities standpoint, although the buffet characteristics were not detected in the remotely controlled model.

In investigations of this nature involving pilot opinion of general flight behavior and covering a matrix of conditions, it is usually desirable to determine and present the results in tabular or graphical form rather than just in word descriptions of the model motions. Table 1 shows the flying model pilot rating system currently in use compared with the Cooper rating system used in full-scale flight work. The use of this system does not imply that the model technique can predict, quantitatively with fine graduation, the full-scale characteristics. Rather, the model ratings are aligned with the Cooper system by use of the $3\frac{1}{2}$ and $6\frac{1}{2}$ boundaries between satisfactory, unsatisfactory, and unacceptable characteristics. The intent of the model ratings is to consider, using past experience, what type of model behavior would represent the behavior required of an airplane to meet the conditions listed under the Cooper system (whether the mission could be accomplished and the aircraft landed; whether flight behavior was acceptable for normal operating conditions or only for emergency conditions) and to present these ratings with a system that would be familiar to most people.

Figure 6 is presented as an example of the results obtained in an investigation of a special problem, such as wing stalling resulting from reduced slipstream velocity over the wing during

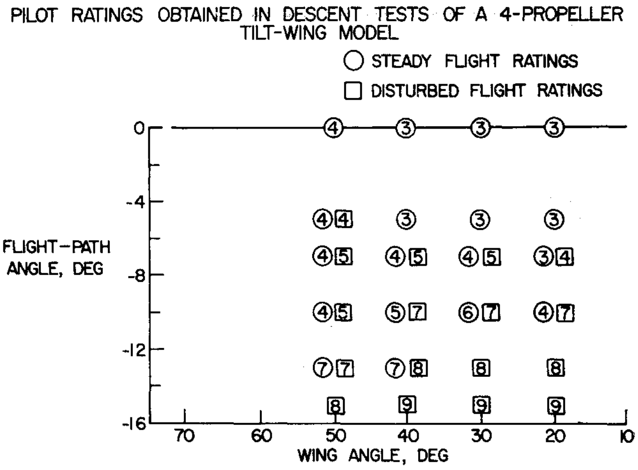

Fig. 6 Pilot ratings obtained in descent tests of a 4-propeller tilt-wing model.

descent flight. Pilot ratings obtained on a flying model of a four-propeller tilt-wing aircraft are shown on a plot of flight-path angle against wing incidence. Ratings were obtained at wing incidences of 20°, 30°, 40°, and 50° for descent angles of 0°, 5°, 7°, 10°, 13°, and 15°. At each point, two ratings were obtained: 1) a rating of the behavior of the model when reasonably smooth and steady flight was maintained, and 2) a rating for disturbed flight after the model had intentionally been given a large disturbance or had been allowed to build up its own large-amplitude disturbed motion. At small descent angles the model was very stable and had to be intentionally disturbed with controls, after which the disturbed motion

Table 1 Comparison of model rating system with Cooper rating system

Flying model pilot rating system		Cooper pilot opinion rating system				
Numerical rating	Description	Description	Primary mission accomplished	Can be landed	Adjective rating	Operating conditions
1	*Extremely easy to fly*—requires no attention to control	Excellent, includes optimum	Yes	Yes	Satisfactory	Normal operation
2	*Very easy to fly*—requires practically no attention to control	Good, pleasant to fly	Yes	Yes		
3	*Easy to fly*—requires very little attention to control	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes		
4	*Not difficult to fly*—requires attention to control	Acceptable, but with unpleasant characteristics	Yes	Yes	Unsatisfactory	Emergency operation
5	*Not too difficult to fly*—requires considerable attention to control	Unacceptable for normal operation	Doubtful	Yes		
6	*Difficult to fly*—requires almost constant attention to maintain flight	Acceptable for emergency condition only[a]	Doubtful	Yes		
7	*Very difficult to fly*—requires constant attention to maintain flight	Unacceptable even for emergency condition[a]	No	Doubtful	Unacceptable	No operation
8	*Extremely difficult to fly*—flyable only with maximum attention given to maintain flight	Unacceptable—dangerous	No	No		
9	*Unflyable*—cannot be flown even with maximum attention given to maintaining flight	Unacceptable—uncontrollable	No	No		
10	*Catastrophic*—model destruction	Motions possibly violent enough to prevent pilot escape	No	No	Catastrophic	

[a] Failure of stability augmenter.

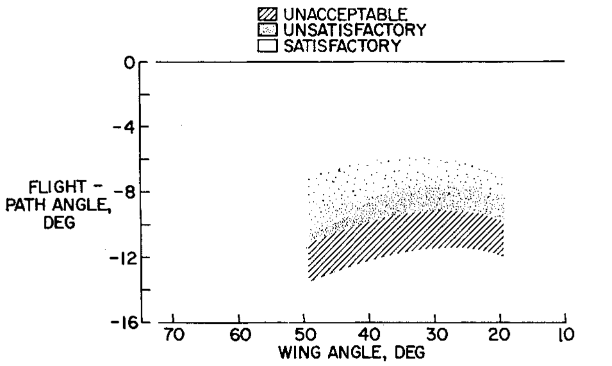

Fig. 7 Descent capability of a 4-propeller tilt-wing model in transition.

damped quickly, and so for these conditions there was no difference between the two ratings. At higher descent angles, around 10°, it was difficult at some wing incidences to establish steady flight conditions; thus two ratings are given. And at the greatest descent angles, steady flight was not possible so that only a disturbed-flight rating was given. The ratings shown in Fig. 6 are over-all ratings obtained from individual ratings on lateral, directional, longitudinal, and power characteristics.

For convenience in discussing the model pilots' interpretation of the results, the ratings can be summarized in the form of boundaries, as in Fig. 7, shown on a plot of flight-path angle against wing-incidence angle. Figure 7 shows a 6° descent capability, above the dotted area, where no difference from level flight was detected even when the model was intentionally disturbed. As the descent angle was increased in the dotted area, the model required more and more pilot attention to the controls, and flow disturbances could be noticed occasionally from tufts. It was felt that, although the model characteristics were not unacceptable in the dotted area, the flow disturbances noticed could mean that buffeting would be a factor in this region of flight for the full-scale aircraft. At the higher descent angles in the dotted area, the model did not settle down quickly after a disturbance, and in the cross-hatched area the model experienced abrupt wing dropping, abrupt losses in height, and the generally sloppy, wallowing motions normally associated with extensive wing stall. It was felt that the characteristics were completely unacceptable in this region. Figure 8 is a graphic example of how the results of stalling show up in the model flights. Time histories of the model motions in controlled flight for level flight and 13° descent flight are shown for a wing incidence of 30°. In each case the angle of roll and angle of yaw is plotted against model time. In level flight the model was very easy to fly and required only occasional corrective control. The erratic, sloppy motions at 13° descent angle, however, were extremely different to control, and, in fact, control of the model was lost at times during the tests.

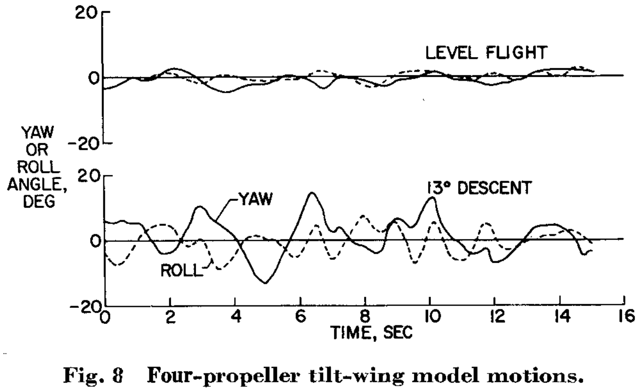

Fig. 8 Four-propeller tilt-wing model motions.

The free-flight model technique also allows the pilots to study other characteristics of the model motions in descent flight that cannot be expressed by simple ratings. For example, at times in the tests of the four-propeller tilt-wing model just reported, the model would drop in height abruptly without any appreciable effect on the lateral-directional characteristics being noted. This abrupt loss in height was a new type of motion not previously experienced with the VZ-2. From watching the tufts on the wing, it was evident that the abrupt dropping was caused by an abrupt symmetrical stall over a large part of both the left and right wing panels. Another characteristic noticed was that, at high descent angles, somewhat different model motions were obtained at low wing incidence than at high wing angles. For example, at 20° wing incidence, steady flight could be achieved quite easily and with no apparent stalling to about 10° descent angle. However, if a disturbance occurred at this point, the resulting abrupt wing dropping and generally sloppy, wallowing motions were very difficult to control and a rating of 7 resulted. At 50° wing incidence, however, the tufts showed disturbed flow on the wing long before the model motions were appreciably affected. This effect can probably be explained by the fact that at the high incidence of the thrustline and high flap deflection at 50° wing incidence, most of the weight was supported by power rather than by wing lift, so that wing stall affected only a very small part of the total lift.

Normally, small-scale tests would not be too suitable for representing the stall or other flight conditions involving separated flows because of the discrepancy in Reynolds number. Experience has shown, however, that the stall of a small-scale model usually occurs at a lower angle of attack than that for the corresponding airplane, and also, when the stall does occur, the resulting motions are generally quite similar. In the case of the descent tests, therefore, it would be expected that the effect of low Reynolds number would tend to give conservative results and that, in any event, the free-flight model technique gives a good qualitative indication of the type of resultant motion expected as the rate of descent is increased.

Control-Line Technique

Forward-flight investigations performed in the full-scale tunnel are limited by the nature of the tunnel drive system to conditions of constant or slowly changing forward speed. There are cases, however, which cannot be investigated properly unless rapid changes in speed can be made. In some of these cases, the effect of large accelerations (or decelerations) on longitudinal stability and control might be the object of the test; in other cases, the speed might have to be changed quickly to match rapid and unavoidable fluctuations in model speed during a transition flight.

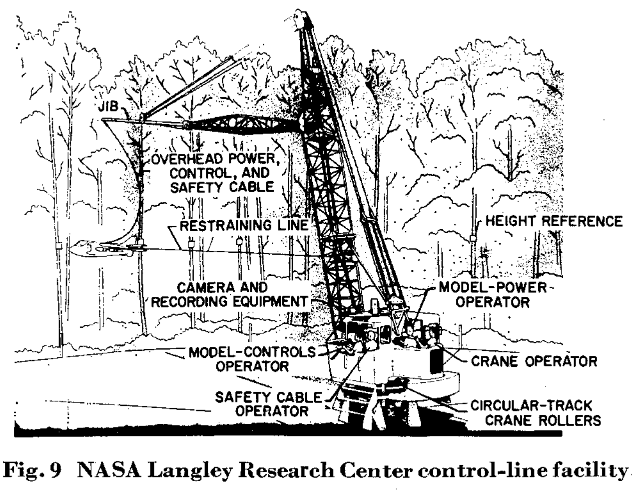

Fig. 9 NASA Langley Research Center control-line facility.

In order to investigate such areas as these, NASA employs a technique in which piloted models are flown in a circular path by means of control-line equipment. The equipment used for the control-line tests is shown in Fig. 9. The model and its flight cable are the same as used for the free-flight investigations described earlier. The test facility itself consists of a standard crane, fitted with a special jib boom, mounted on a concrete base at the center of a 130-ft-diam paved circle. The outer end of the jib boom, located about 30 ft up from the ground and 50 ft out from the axis of rotation of the crane, provides the overhead support and connections for the flight cable. A light steel cable extends from the side of the model to an attachment point on the crane. This cable keeps the model flying in a circular path about the axis of rotation of the crane.

A crew of four men is required to perform tests on the control-line rig. Three of the members are the pitch pilot, the model power operator, and a safety cable operator, whose respective duties are much the same as they were in connection with the free-flight tests. The fourth crew member is the crane operator, whose duty it is to rotate the crane at the rate required to keep the end of the boom vertically over the model at all times during a flight.

A typical flight test (assuming the subject to be a tilt-wing VTOL model) would begin with the model resting on the ground, with its wing tilted up to the takeoff position. The model power operator applies power to the model until it rises from the ground and comes to a steady hovering condition at an altitude of about 15 ft, with the flight cable slack. The pitch pilot, who also controls the wing tilt angle in these tests, then operates the wing-tilting mechanism and the model enters its transition phase. As the model gains forward speed, the crane operator rotates the crane to keep up with the model, and the pitch pilot and power operator attempt to hold the model at a constant altitude. The transition progresses, as in the tunnel tests, until the model has reached its cruise configuration.

An example of the value of these control-line tests is provided by a consideration of the difference in behavior of the VZ-2 model in its tunnel transition tests and its control-line tests. In the tunnel, at a certain point in the transition with the airspeed increasing and the wing being rotated, the model developed a nose-up pitching moment which exceeded slightly the available nosedown control power. The model consequently nosed up, lost some forward speed, and was immediately carried backward by the tunnel airstream until it was stopped by the safety cable. With the control-line technique, under similar conditions of speed and control power, the model again developed the nose-up attitude, and loss of speed. The reduction in speed and continued reduction of wing incidence, however, reduced the nose-up moment to a value less than that of the control power available, with the result that the model successfully passed through this critical phase and completed its transition. The ability of the crane to change speed rapidly enough to follow the model through its irregular speed variation in this area permitted a more realistic view of the longitudinal behavior than the tunnel tests, which were terminated by the initial reduction in model speed. Although the tunnel tests showed a lack of adequate control margin, the control-line tests showed that the transition could be successfully completed with only a slight fluctuation in model attitude and speed with proper pilot techniques.

The primary object of the control-line tests, which is the study of acceleration effects on longitudinal stability and control, is easily achieved because the acceleration capability of the crane (up to $2g$) usually exceeds that of the model itself. The control-line equipment also offers the possibility of studying a model's longitudinal characteristics during conventional or STOL takeoffs and landings, and in forward flight in ground effect, all of which conditions would be impossible to simulate accurately with the existing tunnel setup. The control-line equipment has also made it possible to test models powered with hydrogen peroxide rockets, which from safety considerations would not have been done in the tunnel.

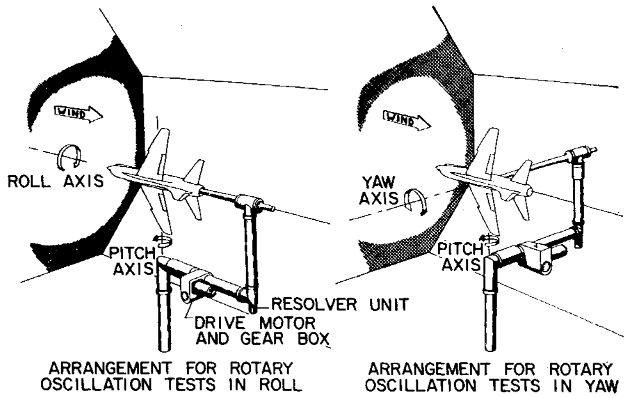

Fig. 10 Schematic sketch of oscillation test apparatus.

Forced-Oscillation Force Tests

For computer or simulator studies, numerical values for dynamic stability derivatives are required. By the use of a technique developed by NASA, it is now possible to measure directly several of the most important derivatives with wind-tunnel equipment that is relatively inexpensive. In this technique, as illustrated in Fig. 10, the model is mounted on a sting which, by means of an electrical drive system, can be made to rotate about its own longitudinal axis in an angular oscillation of adjustable frequency and amplitude. A strain-gage balance connects the model to the sting. Signals from the strain-gage balance are fed into a calibrated resolver system which produces readings directly proportional to the dynamic stability derivatives. This equipment is described in detail in Ref. 3.

The derivatives measured by this forced-oscillation technique are called oscillatory derivatives, and represent a combination of the pure damping derivatives with certain linear-acceleration derivatives. That is, the longitudinal oscillatory derivatives contain C_{M_q} (damping in pitch) and $C_{M\dot{\alpha}}$ (damping due to normal acceleration), and the lateral derivatives contain C_{l_p} or C_{n_r} (damping in roll or yaw) with a $\dot{\beta}$ (lateral acceleration) term. Experience has shown that the use of the combination derivatives gives a more reliable prediction of oscillatory stability characteristics than the use of the pure rate derivatives alone. This is particularly true at the higher angles of attack, where the combination derivative can become large because of the effect of flow separation on the linear-acceleration component of the derivative. For example, for an early delta-wing airplane, calculations based on pure rate derivatives predicted a high degree of Dutch roll instability at high angles of attack whereas free-flight model tests had shown stability. At the time there was no way of knowing which of these two sources of information to credit, since this was a new type of airplane on which there was no experience, since the calculation might be in error because of erroneous assumptions in the equations of motion, and since the estimation of derivatives and the free-flight model results might not predict the correct result because of unknown scale effects. When the airplane was flown, it was found to confirm the results of the free-flight model tests, and it was not until some years later when the forced-oscillation equipment was developed that the source of the error in the calculations was discovered. It was in the use of pure rate derivatives and in neglecting the lateral acceleration or $\dot{\beta}$ derivatives, which were very important at high angles of attack because of the separated flow of delta wings under these conditions.

A proper theoretical treatment, of course, requires that the pure rate and lateral acceleration derivatives be separated and

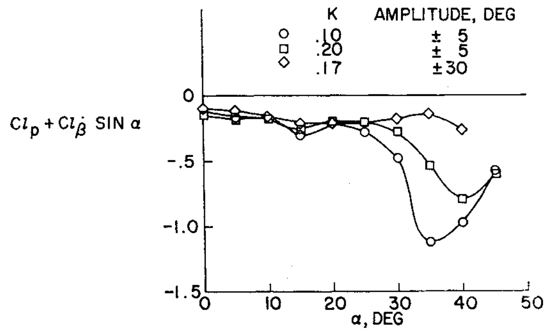

Fig. 11 Effect of frequency and amplitude on an oscillatory derivative.

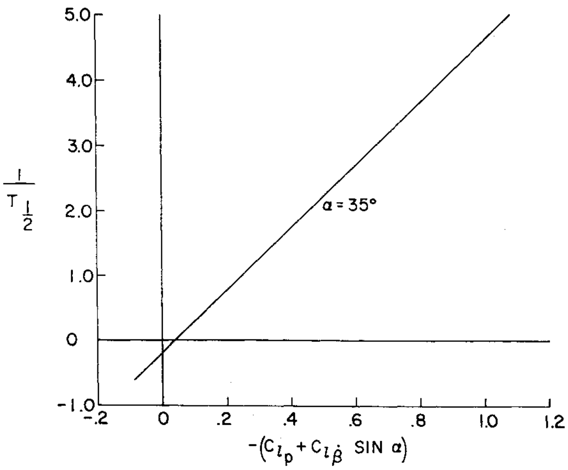

Fig. 12 Effect of variation of $C_{s_p} + C_{s_\beta}$ sinα.

included separately in the equations of motion. So far, however, it has not been possible to separate these derivatives with any accuracy. Such separation requires the measurement of one of the derivatives separately, so that it can be subtracted from the combined derivatives measured by the forced oscillation technique, but the equipment for the measurement of one of the separate derivatives is not at hand. Experience has shown, however, that reasonably good accuracy in dynamic stability calculations can be obtained if the derivatives are used correctly in combined form. The evaluation of the derivatives is relatively straightforward in the low-lift coefficient range, but at lift coefficients near the stall a serious complication develops. At these lift coefficients near the stall, the lag in the alternating increase and decrease in separated flow on the wing surfaces produces moments out of phase with the oscillation, and causes the derivatives to become functions of the frequency and amplitude of the oscillation. Figure 11 shows a typical variation of an oscillatory derivative with angle of attack, frequency, and amplitude. It is obvious that you could not have calculated the motions correctly unless great care had been taken in choosing the appropriate derivative in the stall range. As an illustration, Fig. 12 shows the damping of a lateral oscillation as calculated using the range of experimentally determined values for the oscillatory derivative $C_{l_p} + C_{l_{\dot\beta}}$ sinα.

Figures 11 and 12 show that it is important to measure the oscillatory stability derivatives at frequencies and amplitudes representative of the motions likely to be encountered by the configuration under study. As an aid in choosing representative values, the natural frequency of a configuration can be approximated through considerations of its mass, inertia, and static characteristics. As far as the amplitude of the oscillation is concerned, most published information to date presents derivatives based only on small-amplitude oscillations. For configurations having high values of inertia and damping, it is likely that small-amplitude derivatives will be appropriate for predicting dynamic stability characteristics, but for configurations having low inertia and low damping there is more likelihood that large amplitude motions may be encountered. Therefore, derivatives measured at large amplitude may be more useful in predicting dynamic stability characteristics in these cases. Most of the difficulties arising from measuring the derivatives at an inappropriate amplitude can be avoided by making the measurements over a range of amplitudes. The results of calculations based on the resulting values of the derivatives may then be compared and interpreted to yield usefully accurate predictions of full-scale behavior.

The interpretation of the forced-oscillation tests must include a consideration of Reynolds number effects. The preceding discussion has attempted to point out the large effects that the stall can have on the value of the stability derivatives. Because the variation of stall angle with lift coefficient is a function of Reynolds number, it follows that the dynamic stability characteristics may also change with Reynolds number. It has been found that the change consists of what might be termed a slight shift to a higher angle of attack of that part of the curve of some stability parameter plotted against angle of attack which is dependent on stall characteristics. The model will predict trends in full-scale behavior with considerable accuracy, but its prediction of the angle of attack at which some given characteristic may be expected will usually be somewhat low.

Summary

Historically, free-flight model tests have been found to be a very useful technique for exploratory research on novel configurations to discover the gross stability and control characteristics and the general means of solving the problems. They are not so useful for detailed stability studies in well-defined areas. Stability calculations and computer studies are much more useful for such detailed studies but require the input of accurate stability derivatives. The forced-oscillation method of measuring these stability derivatives and the means of using these derivatives described herein have proved to be very helpful in such analytical studies.

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