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ANALYSIS OF FACTORS INFLUENCING THE STABILITY CHARACTERISTICS OF SYMMETRICAL TWIN-INTAKE AIR-INDUCTION SYSTEMS

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SUMMARY

An analysis is made of the factors influencing the flow instability and flow reversal which has been encountered experimentally at low inlet-velocity ratios with several twin-intake air-induction systems. It is shown that the flow instability and flow reversal are functions of the static-pressure-recovery characteristics at the juncture of the two ducts. The method of analysis provides a means of predicting the inlet-velocity ratio for flow instability and the inlet-velocity ratio for flow reversal. Predicted results are in good agreement with the available experimental data.

INTRODUCTION

Experimental investigations of air-induction systems in which the air flows of two intakes join in a common duct have indicated that many of these systems are subject to air-flow instability at low inlet-velocity ratios. A particular type of instability, which is characterized by fluctuations of the quantity of flow in each duct and which usually results in reversal of flow in one of the ducts as the system-inlet-velocity ratio is reduced further, is the subject of this analysis. It has been observed that this flow instability occurred when the intake pressure-recovery characteristics were such that over a portion of the inlet-velocity-ratio range the ram-pressure recovery increased with an increase of inlet-velocity ratio.

The generally accepted qualitative explanation for the instability is based on the ram-pressure-recovery characteristics of the system and is as follows:

1. Consider that the intakes are symmetrical, geometrically and aerodynamically, and are operating at a system mass flow where the ram-pressure recovery is increasing with an increase of inlet-velocity ratio.

A disturbance, such as a boundary-layer fluctuation, which would change the aerodynamic symmetry would result in a decrease of inlet-velocity ratio in one intake and an increase in the other. The intake having the initial decrease of inlet-velocity ratio would have a decreased ram-pressure recovery which in turn would tend to decrease further the mass flow of that intake. The intake having the initial increase of inlet-velocity ratio would have an increased ram-pressure recovery which would tend to increase further the mass flow of that duct. As a result, the intakes would continue to operate at increasingly different inlet-velocity ratios and the possibility of flow reversal in one of the intakes would exist. Thus, the ram-pressure recovery which increases with increasing mass-flow ratio has a destabilizing effect on the air flow through the ducts.

2. By similar reasoning, it can be shown that the variation of ram-pressure recovery would have a stabilizing effect on the air flows with the system operating at inlet-velocity ratios at which the ram-pressure recovery decreases with an increase of inlet-velocity ratio.

The foregoing explanation is not entirely satisfactory because it gives no quantitative indication of the inlet-velocity ratio for flow instability or that for flow reversal. Furthermore, it is not demonstrated that an explanation should be based on the ram-pressure-recovery characteristics. Therefore, an analysis has been made to determine a proper basis for an explanation and to provide a more quantitative explanation of the flow instability and the flow reversal. This report presents the results of this analysis.

NOTATION

The symbols used throughout this report are defined as follows:

A	duct area, square feet
p	static pressure, pounds per square foot
q	dynamic pressure, pounds per square foot
V	velocity of the air stream, feet per second
ΔH	loss of total pressure between any two designated stations, pounds per square foot
ρ	mass density of the air, slugs per cubic foot
φ	angle between the flow direction of the air in two adjoining ducts

Subscripts

o	free-stream conditions
1	conditions at the duct inlet
2	conditions at the juncture of the two ducts
3	conditions at a very small but finite distance downstream of the juncture of the two ducts
a	conditions in duct a
b	conditions in duct b
ind	individual
sys	system

Parameters

V_1/V_o	inlet-velocity ratio
q/q_o	dynamic-pressure ratio
$\frac{p - p_o}{q_o}$	static-pressure recovery
$1 - \frac{\Delta H}{q_o}$	ram-pressure recovery

THEORY AND APPLICATION OF THE ANALYSIS

In principle, the method of analysis is relatively simple. The twin-intake air-induction system and its flow characteristics have been treated in a manner similar to that used for analysis of flow in dividing pipes. In the case of the twin-intake system (fig. 1), the point of division is in the undisturbed stream ahead of the model (station 0). The point of rejoining is at the juncture of the two ducts (station 2). We may relate the flow between station 0 and station 2 of each duct by means of the Bernoulli equation. If the flow is assumed to be incompressible, this relation is shown by

$$p_{2_a} + \frac{\rho V_{2_a}{}^2}{2} + (\Delta H_{o-2})_a = p_o + \frac{\rho V_o{}^2}{2} \tag{1}$$

and

$$p_{2_b} + \frac{\rho V_{2_b}{}^2}{2} + (\Delta H_{o-2})_b = p_o + \frac{\rho V_o{}^2}{2} \tag{2}$$

Equations (1) and (2) may be transformed into a more convenient form by rearranging the terms, by dividing by the free-stream dynamic pressure, and by expressing the velocity at station 2 in terms of the inlet velocity V_1 as follows:

$$\frac{p_{2_a} - p_o}{q_o} = 1 - \left[\frac{(\Delta H_{o-2})_a}{q_o}\right] - \left(\frac{A_1 V_1}{A_2 V_o}\right)_a^2 \tag{3}$$

$$\frac{p_{2_b} - p_o}{q_o} = 1 - \left[\frac{(\Delta H_{o-2})_b}{q_o}\right] - \left(\frac{A_1 V_1}{A_2 V_o}\right)_b^2 \tag{4}$$

The next step is to determine the relation between the flows in the two ducts. A relation may be established on the basis of the following two assumptions:

1. The two flows have a common static pressure immediately after joining (station 3).

2. The static pressure at station 3 is essentially equal to the static pressure at the terminus (station 2) of each individual duct.

The validity of these assumptions will be discussed later.

With the static pressures p_{2_a} and p_{2_b} equal to each other, equation (3) can be set equal to equation (4), thus

$$\left[1 - \frac{(\Delta H_{o-2})_a}{q_o}\right] - \left(\frac{A_1 V_1}{A_2 V_o}\right)_a^2 = \left[1 - \frac{(\Delta H_{o-2})_b}{q_o}\right] - \left(\frac{A_1 V_1}{A_2 V_o}\right)_b^2 \tag{5}$$

Since

$$\left(\frac{A_1 V_1}{A_2 V_o}\right)^2 = \frac{q_2}{q_o}$$

it may be seen from equation (5) that the quantity of flow in duct a can be different from that in duct b, provided that the resulting difference in dynamic-pressure ratio at station 2, $\frac{q_2}{q_o}$, is equal to the difference in ram-pressure recovery of the two ducts.

The flow-instability and flow-reversal characteristics can be determined most readily by a graphical application of the analysis. An example of this procedure as applied to an assumed system having the characteristics shown in figure 2 is given in the following discussion:

In figure 2(a), the total-pressure-recovery and the static-pressure-recovery characteristics at station 2 are shown for each duct operating independently. Since it has been assumed that the static pressures of the two ducts are equal at station 2, the inlet-velocity ratios at which each duct will operate in combination with the other can be determined by following lines of constant static-pressure recovery. It may be noted that the minimum system-inlet-velocity ratio for stable flow is the inlet-velocity ratio for maximum static-pressure recovery, 0.55. At system-inlet-velocity ratios higher than 0.55 the requirement for uniform static pressure at station 2 can be satisfied only with equal quantities of flow in the two ducts and, therefore, the quantity of flow in each will tend to remain constant. At system-inlet-velocity ratios below 0.55, the requirements of a uniform static pressure at station 2 may be satisfied with either equal quantities of flow in the two ducts or at some point with unequal quantities of flow in the two ducts. As a result, there will be a tendency for fluctuation of flow in the ducts. For example, with the system operating at point 1, an inlet-velocity ratio of 0.45, the individual inlets could be both operating at an inlet-velocity ratio of 0.45 or one could be operating at point 2, an inlet-velocity ratio of 0.19, with the other operating at point 3, an inlet-velocity ratio of 0.71. As will be explained later, the intakes tend to operate at points 2 and 3 once the aerodynamic symmetry is disturbed.

At given inlet-velocity ratios for the assumed system, the predicted values of inlet-velocity ratio of each duct then can be shown as in figure 2(b). The portion of the curve above a system-inlet-velocity ratio of 0.55 is in the stable flow region in which the predicted inlet-velocity ratio of each duct is the same as the system-inlet-velocity ratio. Below a system-inlet-velocity ratio of 0.55 the two diverging curves represent the predicted values of individual inlet-velocity ratio for ducts a or b. The dashed line represents the individual inlet-velocity ratios of ducts a and b in the unstable region if the flow symmetry is not disturbed. The indicated individual inlet-velocity ratios at points 1, 2, and 3 are the same as those shown in figure 2(a). In decreasing the system-inlet-velocity ratio to 0.40, the flow through one duct becomes zero and reversal of flow is imminent. Thus, the inlet-velocity ratio for flow reversal can be determined.

DISCUSSION OF THE ANALYSIS

Assumptions

The major assumptions of the analysis were that the static pressure is uniform across station 3 and is equal to that at station 2. Therefore, the ability of the analysis to predict the inlet-velocity ratios for flow instability and for flow reversal depends on the validity of these assumptions regarding the static pressure. Although their validity has not been determined experimentally for twin-intake systems, the assumptions appear to be reasonable when the possible flow conditions are compared to flow patterns for which experimental data have been obtained. For example, with zero flow in one of the ducts, such as shown in figure 3(a), the flow pattern becomes similar to that with a sudden expansion of cross-sectional area. Theoretical determination of losses encountered with this type of a sudden expansion has been made satisfactorily by use of the assumption that the static pressure just after discharge is equal to the static pressure just before discharge and is constant across the discharge section. An analogy can also be made between the flow patterns of a jet discharging into a stream and those encountered with both equal and unequal division of flow between the two ducts (figs. 3(b) and 3(c)). It has been observed in numerous experiments that the measured static pressure across the discharge section of a jet is relatively constant and is close to that of the stream. The foregoing analogies could similarly be made for a twin-intake air-induction system in which the two ducts empty into a plenum chamber. (See fig. 3(d).)

The validity of the assumptions concerning the static pressure would seem to depend upon the distance between the two duct outlets and upon the angle φ at which the two ducts join. For most twin-intake air-induction systems the angle of joining and the distance between the two duct outlets are small. Care should be exercised, however, in applying this analysis to twin-intake systems where the angle of joining or distance between the duct outlets are of considerable magnitude, or for any case where the static pressures at station 2 in each duct obviously would differ.

Values of the inlet-velocity ratios for flow instability and for flow reversal could be determined from equations (3) and (4) by assuming that the air flows of the two ducts have a common total pressure immediately after joining. Experimental results have shown, however, that this assumption regarding total pressure is not valid. Therefore, quantitative analysis of flow instability and flow reversal cannot be based correctly on the total- or ram-pressure recovery characteristics of the intake system.

In all of the foregoing analysis, the flow was assumed to be incompressible in order to simplify the equations. Calculations indicate that the inclusion of compressible effects in the analysis negligibly alter the predicted values of inlet-velocity ratio for flow instability and for flow reversal. For example, application of corrections for compressibility at a Mach number of 0.8 would result in the predicted inlet-velocity ratio for flow instability being unchanged and the predicted inlet-velocity ratio for flow reversal being increased by 0.02 for the assumed air-induction system.

Instability

In the example illustrating the graphical application of the method, it was shown that a region exists where the ducts can operate in either a balanced condition or an unbalanced condition leading to reversal of flow in one duct. It remains to be demonstrated which of these two conditions is more likely to occur.

It appears impossible to establish quantitatively which flow pattern is more likely to exist since transient flow conditions must be considered. However, it is possible to examine the problem qualitatively and reach conclusions verified by experiment.

As in any problem where the question of stability is involved, the general approach is to place the system in a steady state, impose a momentary disturbance, and examine its effect. In this case let the steady state represent a condition where the system-inlet-velocity ratio is such that the two flow patterns are possible but that the one existing is that of equal flow in the ducts. Now impose momentarily a disturbance which results in a difference in the total pressure between the two ducts. Because equal static pressures exist at the point of joining, the difference in total pressure will result in a different flow quantity in each duct in order to satisfy the relation between total, dynamic, and static pressures. Since a constant system mass flow is to exist, one duct will have a slightly increased flow and the other will have a slightly decreased flow after the disturbance has disappeared. Examination of the static-pressure-recovery curves for each duct will show that under a steady-state operating conditions the two ducts will have different static-pressure-recovery values for these different flow rates. This condition has been assumed inadmissible; hence, it must be presumed that the resultant static pressure for this transient unbalanced condition tends toward an average of the two steady-state values. If this effect occurs, in a case where the static-pressure recovery increases with mass flow, it is apparent that the duct with the higher inlet-velocity ratio will have a lower than steady-state static-pressure recovery and the duct with the lower inlet-velocity ratio will have a higher than steady-state value. Again, in order to satisfy the relation between total, dynamic, and static pressures, the flow rate or dynamic pressure must increase in the duct with greater flow and decrease in the duct with lesser flow. Thus, the flow rates in the two ducts will tend to diverge as a result of the averaging process and character of the static-pressure-recovery variation with mass flow. The greatest difference in steady-state static-pressure recoveries, and hence unbalancing forces due to averaging tendencies, is reached when the duct with the greater flow has its maximum static-pressure recovery. Beyond this point, greater differences in inlet-velocity ratio brings the steady-state static-pressure-recovery values closer together. Hence, the unbalancing forces due to the averaging process decrease and finally disappear as the condition of equal steady-state static-pressure recoveries is reached. Similar reasoning will show that a small momentary disturbance applied with the system in this unbalanced condition will result in forces tending to return the system to the unbalanced condition. It can be seen, however, that a sufficiently large disturbance tending to balance the flow can cause the ducts to reverse their position in the condition of unbalance. The closer the system mass flow is to the point of maximum static-pressure recovery, the smaller the disturbance need be to reverse the position of unbalance. Thus, in this region a twin-duct system may have first one duct then the other carrying the greater flow with no evidence of stable unbalance.

Over the portion of the inlet-velocity-ratio range in which the static-pressure recovery increases with increasing inlet-velocity ratio, a twin-duct system can be disturbed from a balanced condition by a very small disturbance, and hence a balanced condition in this range can be considered unstable. Since momentary aerodynamic asymmetry is likely to exist, it can be concluded that a twin-duct system is more likely to operate in an unbalanced condition in this unstable range.

Factors Influencing Instability and Reversal

Since the system-inlet-velocity ratios for flow instability and for flow reversal are functions of the static-pressure recovery, it can be shown by use of equations (3) and (4) that these inlet-velocity ratios are partially dependent upon the ratio of the areas at stations 1 and 2 (i.e., the amount of diffusion) and upon the total-pressure loss from stations 0 to 2. The total-pressure loss from stations 0 to 2 is composed of the duct loss from stations 1 to 2 as well as the inlet loss from stations 0 to 1. Since the duct loss is somewhat dependent upon the amount of diffusion, the exact evaluation of the independent effect of these two factors on the inlet-velocity ratios for flow instability and for flow reversal becomes difficult. However, it may be stated, in general, that for a given inlet configuration the inlet-velocity ratios for flow instability and for flow reversal decrease with an increase of duct losses and with a decrease of diffusion before joining of the two air flows.

COMPARISON WITH EXPERIMENT

Verification of this quantitative analysis by comparison with experimental results is obviously desirable. The data available to make the comparisons are meager. It has been possible, however, to apply this analysis to two dissimilar air-induction systems for which some data were available. The ducting arrangements and pressure-recovery characteristics of these systems are shown in figure 4. In each case the static pressure at station 2 was computed from known values of total and dynamic pressure at station 2.

Comparisons of the predicted and measured inlet-velocity ratios of each intake for the two systems are shown in figure 5. The dashed lines indicate the predicted values of inlet-velocity ratio for each intake, and the experimental points are indicated by the symbols. The predicted results were in good agreement with the experimental results. It is interesting to note that, with the system for which more complete data were available, the reversal of flow did not always occur in the same duct when test conditions were repeated. (See fig. 5(a).)

The agreement between the predicted and measured values of inlet-velocity ratio for these two systems indicates that the static-pressure assumptions made in the analysis were satisfactory for predicting the inlet-velocity ratios for flow instability and for flow reversal.

CONCLUSIONS

In the analysis of factors influencing the stability characteristics of twin-intake air-induction systems, it is shown that:

1. The flow instability and the flow reversal encountered at low inlet-velocity ratios are functions of the static-pressure-recovery rather than ram-pressure-recovery characteristics at the juncture of the two ducts.

2. The method of analysis provides a means of predicting the inlet-velocity ratio for flow instability and the inlet-velocity ratio for flow reversal.

3. The method of analysis gives results which are in good agreement with the available experimental data.

National Advisory Committee for Aeronautics,
Ames Aeronautical Laboratory,
Moffett Field, Calif., January 5, 1950.

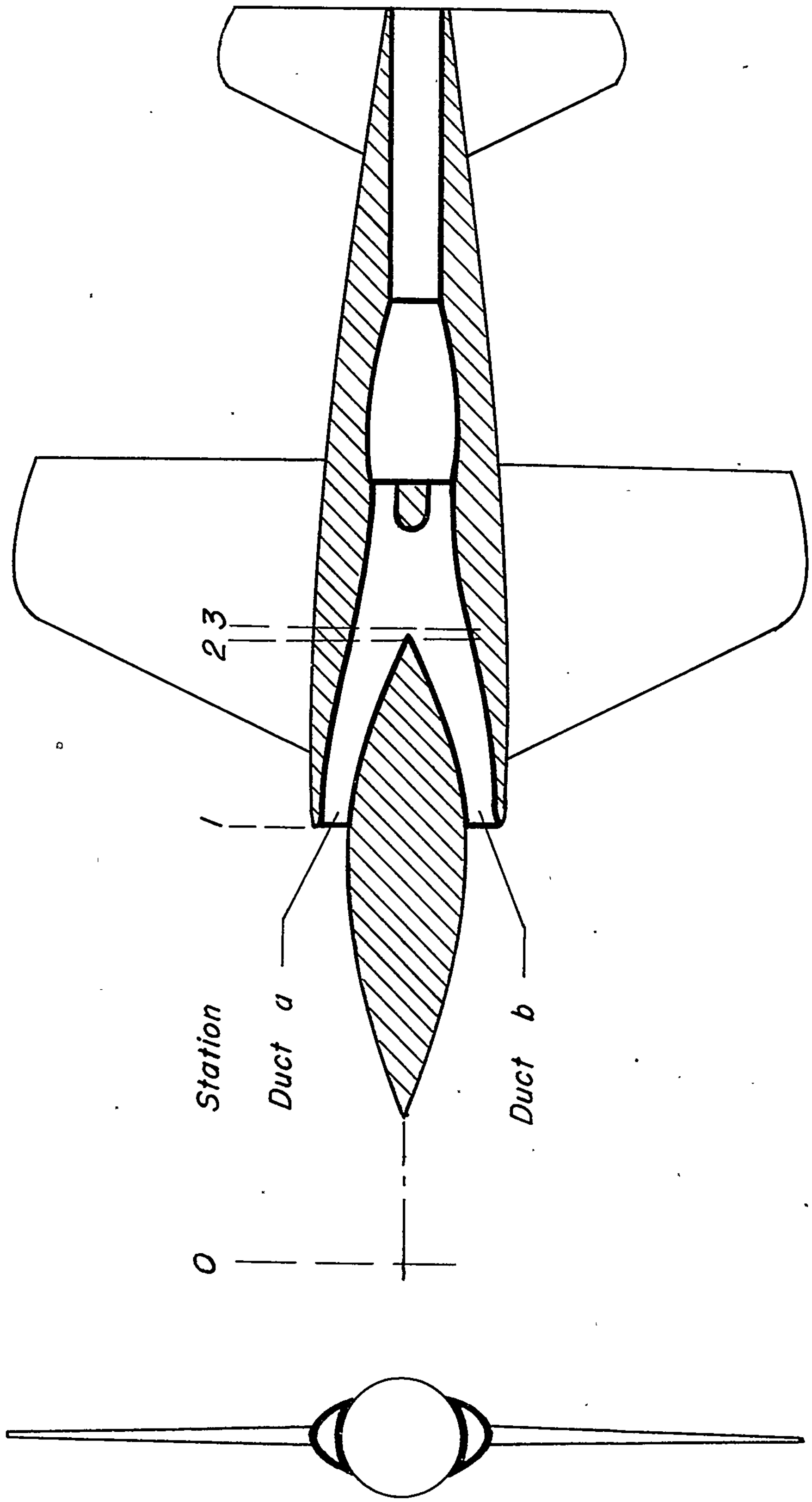
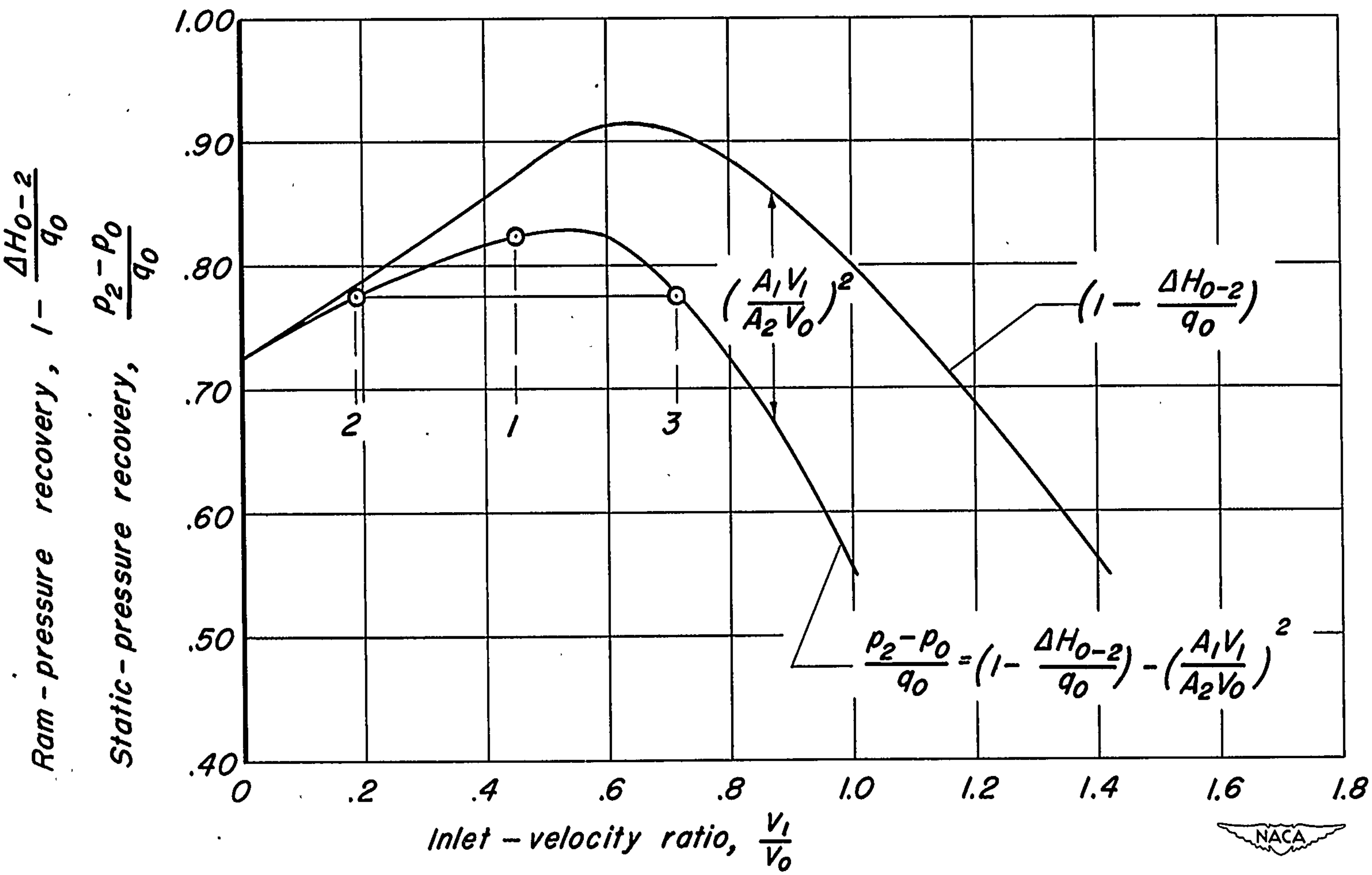
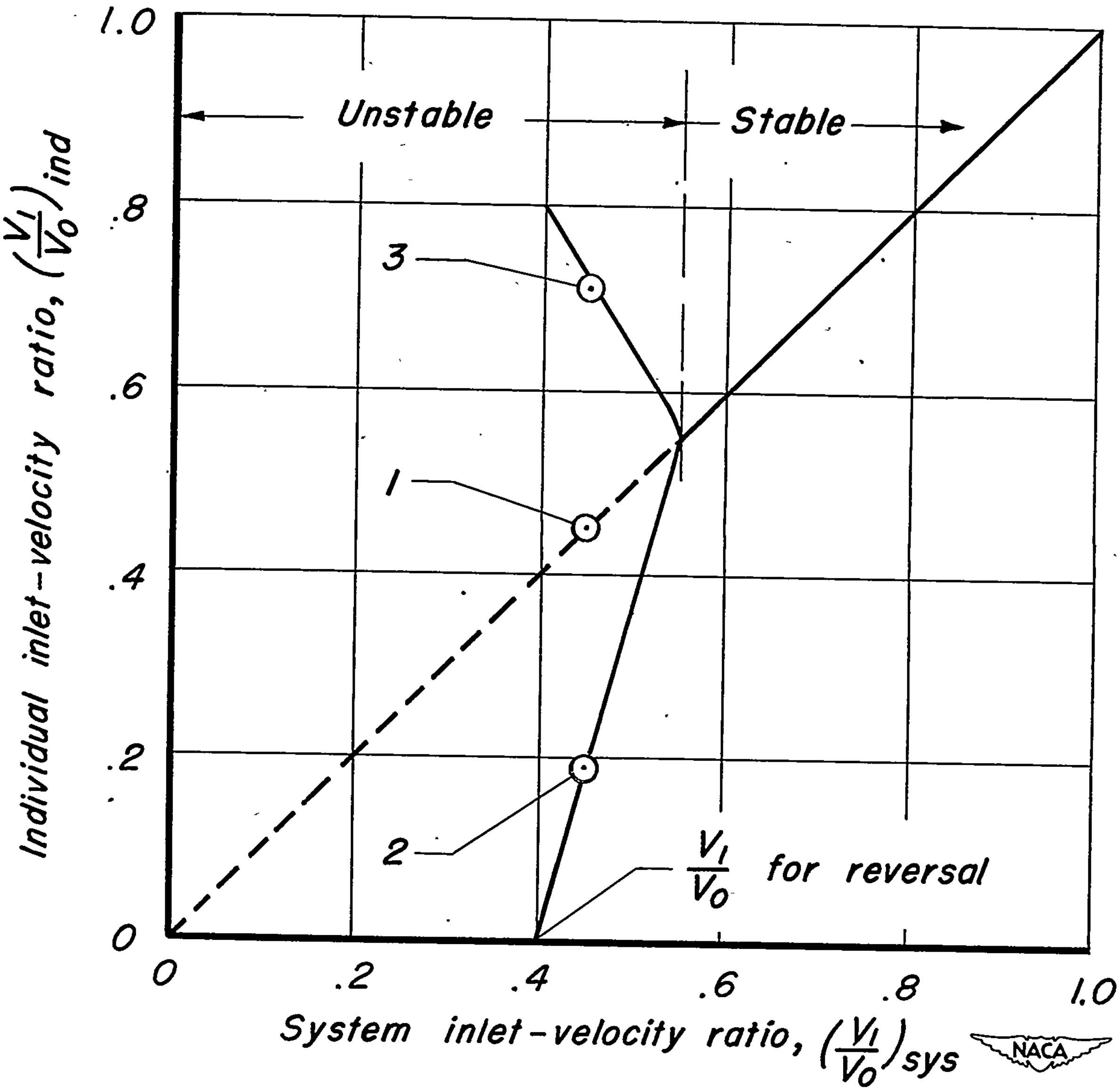


Figure 1.— Typical twin – intake air–induction system.



(a) Assumed pressure-recovery characteristics.

Figure 2.– Pressure–recovery and air–flow characteristics of an assumed twin–intake air-induction system.



(b) Predicted air-flow characteristics.

Figure 2.— Concluded.

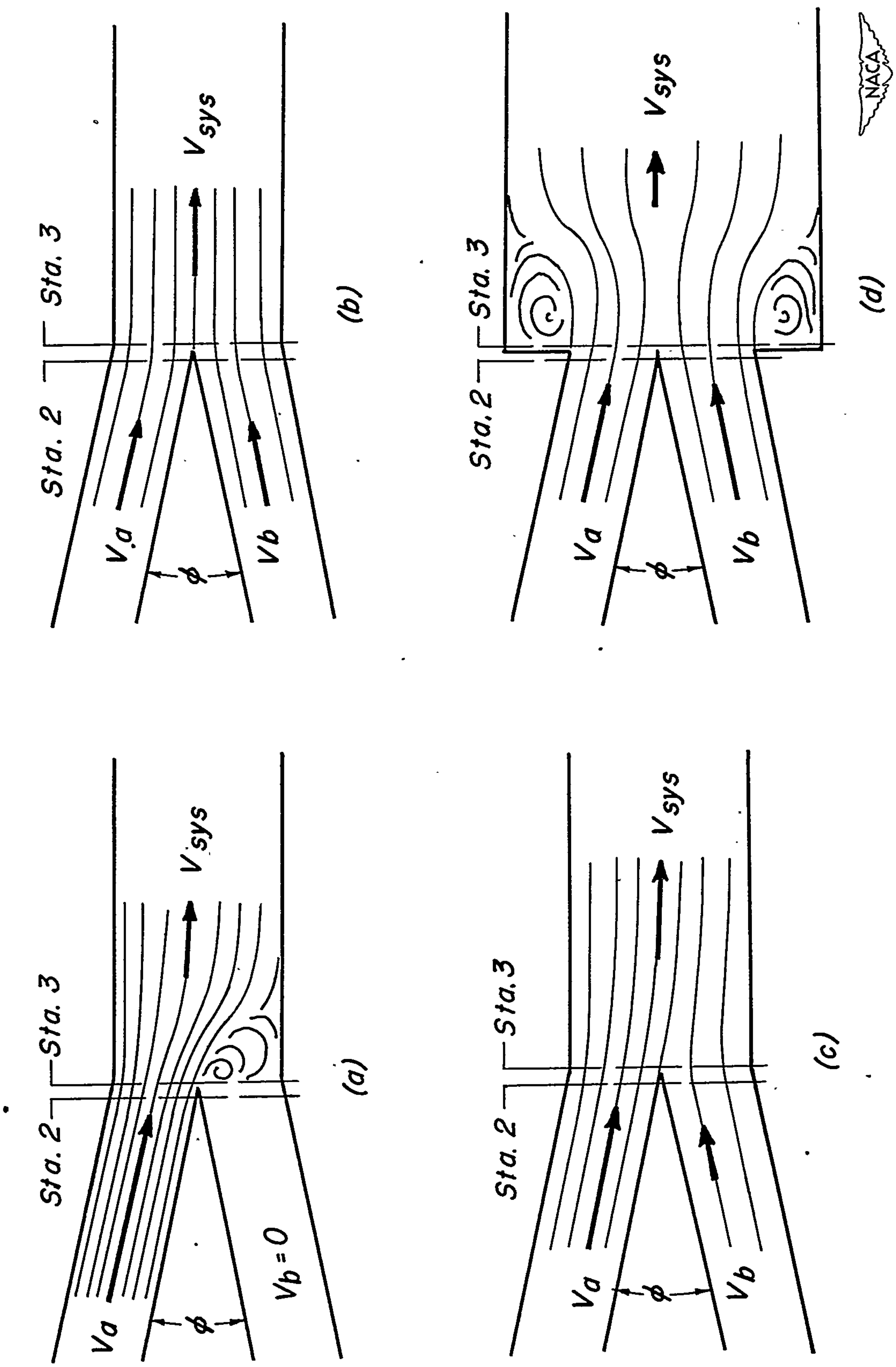
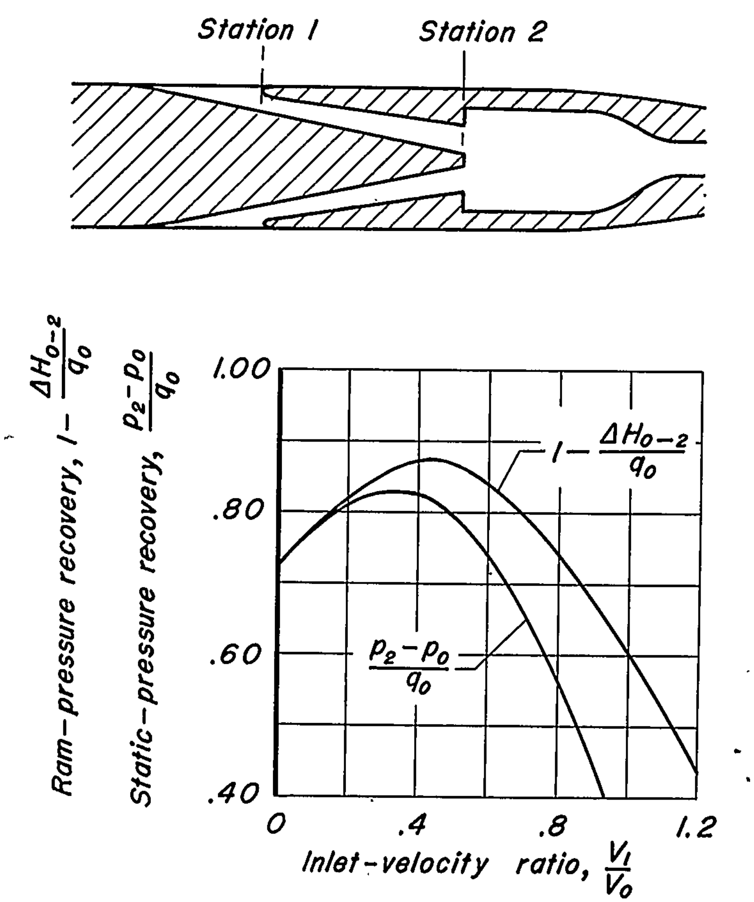
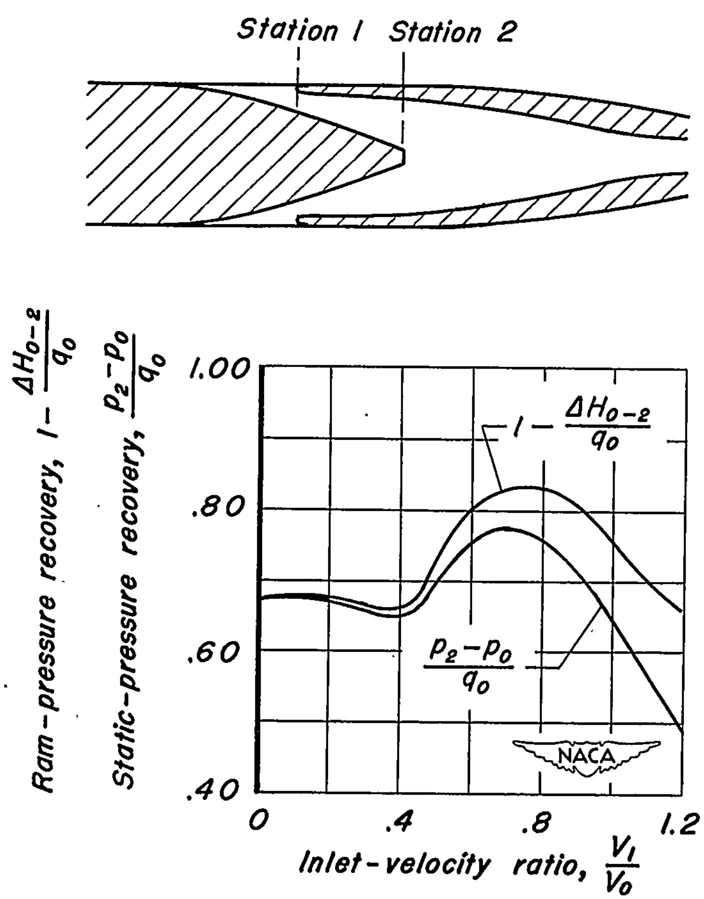


Figure 3.— Flow patterns possible in twin-intake air-induction systems.



(a) Model 1.



(b) Model 2.

Figure 4.— Ducting arrangement and pressure-recovery characteristics of two dissimilar twin-intake air-induction systems.

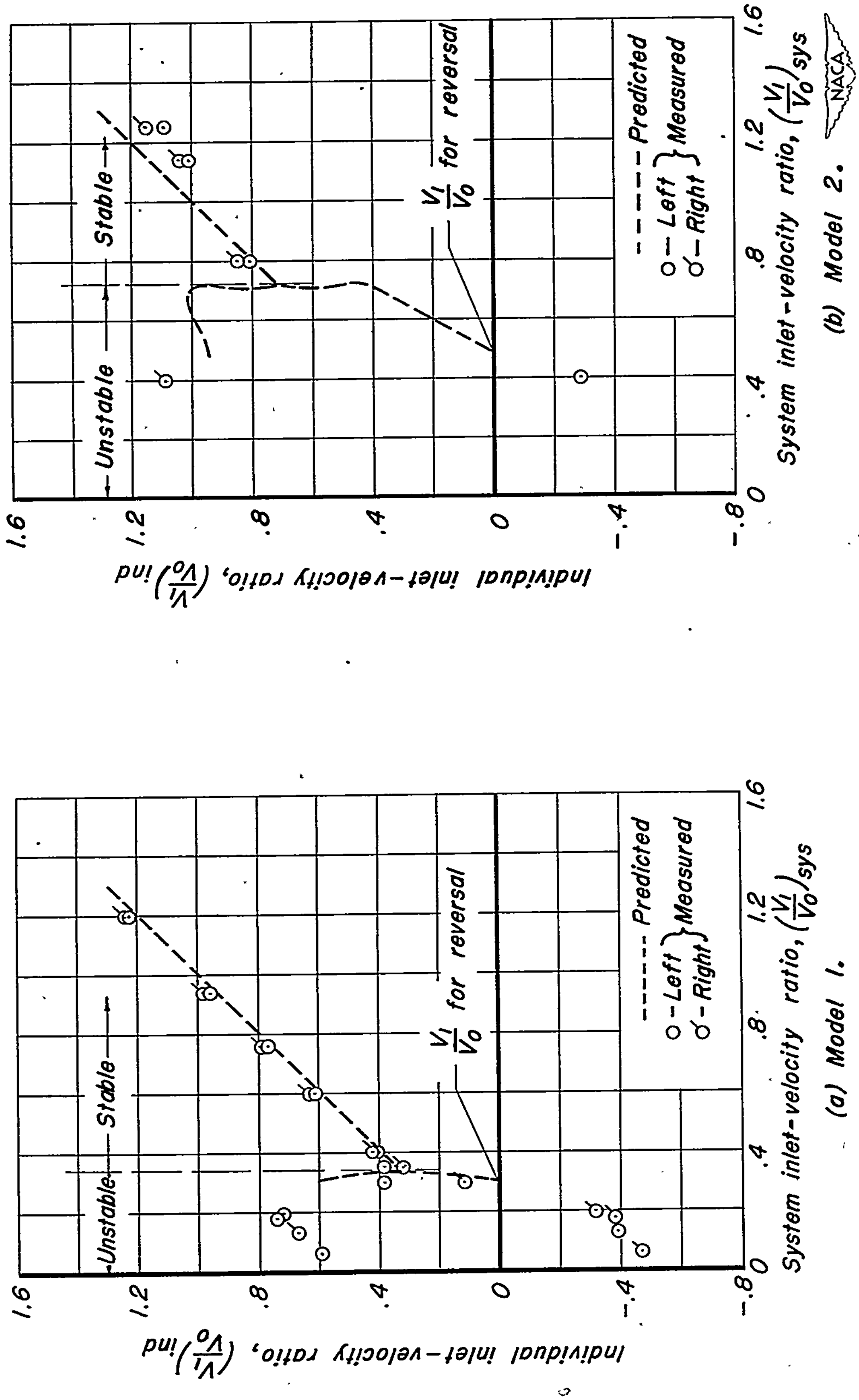


Figure 5.—A comparison of the predicted and measured inlet-velocity ratios of each intake for two dissimilar twin-intake air-induction systems.