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RESEARCH MEMORANDUM

for the

~~Air Materiel Command, Army Air Forces~~

THE EFFECTIVENESS AT HIGH SPEEDS OF A 20-PERCENT-CHORD PLAIN TRAILING-EDGE FLAP ON THE NACA 65-210 AIRFOIL SECTION

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

An analysis has been made of the lift-control effectiveness of a 20-percent-chord plain trailing-edge flap on the NACA 65-210 airfoil section from section lift-coefficient data obtained at Mach numbers from 0.3 to 0.875. In addition, the effectiveness of the plain flap as a lift-control device has been compared with the corresponding effectiveness of both a spoiler and a dive-recovery flap on the NACA 65-210 airfoil section.

The analysis indicates that the plain trailing-edge flap employed on the 10-percent-thick airfoil at Mach numbers as high as 0.875 retains at least 50-percent of its low-speed lift-control effectiveness, and is sufficiently effective in lateral control application, assuming a rigid wing, to provide adequate airplane rolling characteristics.

The plain trailing-edge flap, as compared to the spoiler and the dive-recovery flap, appears to afford the most favorable characteristics as a device for controlling lift continuously throughout the range of Mach numbers from 0.3 to 0.875.

At Mach numbers above those for lift divergence of the wing, either a plain flap or a dive-recovery flap may be used on a thin airplane wing to provide auxiliary wing lift when the airplane is to be controlled in flight, other than in dives, at these Mach numbers. The choice of a lift-control device for this use, however, should include the consideration of other factors such as the

increments of drag and pitching moment accompanying the use of the device, and the structural and high-speed aerodynamic characteristics of the airplane which is to employ the device.

INTRODUCTION

Among many effects of compressibility which have been found in flight and in the wind tunnel is a large reduction in the effectiveness of conventional airplane control surfaces at velocities considerably above the airfoil critical speeds. In some instances the effectiveness has been shown to reduce to nearly zero at high speeds, thus definitely limiting the maximum speed of controlled flight. In order to determine whether this reduction in effectiveness is influenced by the type of control surface employed, various lift-control devices on relatively thin airfoils have been investigated at high speeds.

The lift-control effectiveness of spoilers and dive-recovery flaps used on thin airfoils has been reported in references 1 and 2. The spoilers became decreasingly effective with increasing projection at high Mach numbers, and exhibited characteristics which were such as to promote erratic lift control at high speeds. The dive-recovery flaps also showed generally unfavorable characteristics for use, other than emergency, as lift-control devices at high speeds. Wind-tunnel data presented in reference 3 for a plain trailing-edge flap on a modified NACA 6-series airfoil 19 percent thick indicated that the effectiveness of a plain flap used for lateral control on a thick airfoil rapidly decreases as the Mach number is increased above the airfoil critical Mach number.

In order to provide information on the lift-control effectiveness of a plain trailing-edge flap on a representative thin NACA 6-series airfoil, the present analysis was undertaken. For comparative purposes, increments of section lift, drag, and pitching-moment coefficients for the plain flap together with the corresponding characteristics of the spoiler and the dive-recovery flap are presented for the range of Mach numbers from 0.3 to 0.875. The analysis pertaining to the plain flap was made using data from reference 4. The effect of the differences in rigidity of the wind-tunnel models and the various parts of an airplane has not been considered in the present analysis.

SYMBOLS

c_l	section lift coefficient
Δc_l	increment or decrement in section lift coefficient
Δc_d	increment in section drag coefficient
$\Delta c_{m_{c/4}}$	increment in section moment coefficient about quarter-chord point
M	free-stream Mach number
α_o	section angle of attack, degrees
δ_f	flap deflection, degrees
$\Delta\alpha_o/\Delta\delta_f$	section lateral-control-effectiveness parameter, absolute value of the ratio of equivalent change in section angle of attack to change in flap deflection angle at a constant section lift coefficient

METHODS OF ANALYSIS

The present analysis of flap effectiveness was made using aerodynamic data obtained in the Ames 1- by $3\frac{1}{2}$-foot high-speed wind tunnel from tests of the NACA 65-210 airfoil equipped with a 20-percent-chord plain flap. These data were obtained for speeds ranging from 0.3 to approximately 0.9 Mach number (with a corresponding range in Reynolds numbers from approximately 1×10^6 to 2×10^6) for airfoil angles of attack from -2° to 8° and flap deflections from -6° to 6°. More precisely, the flap deflections in degrees were found to be -6.3, -4.9, -2.6, 0, 1.9, 4.6, and 6.3. The lift-coefficient data for a Mach number of approximately 0.9 were not obtained at a sufficient number of airfoil angles of attack to permit their use in the present analysis. For this reason, only data for Mach numbers as high as 0.875 appear in the figures.

In order to indicate the effectiveness of the plain flap as a lift-producing device, increments of section lift coefficient for each angle of flap deflection have been determined. These increments were obtained throughout the Mach number range at airfoil angles of attack corresponding to lift coefficients of 0, 0.2, 0.4, 0.6,and 0.8 at zero flap deflection. Faired curves showing these increments for constant Mach numbers are presented in figure 1 as a function of flap deflection. The same increments for constant flap deflection cross-plotted at each airfoil angle of attack given in figure 1 are presented in figure 2 as a function of Mach number.

The effectiveness of a lateral-control device is not indicated completely by increments of lift coefficient alone. Some parameter must be used which considers the changes in airfoil lift-curve slope with changes in control surface deflection. The commonly used parameter $\Delta\alpha_o/\Delta\delta_f$, defined as the ratio of the change in airfoil-section angle of attack to the change in flap deflection necessary to maintain a constant lift coefficient, has been adopted for use in the present analysis. The variation of this parameter with Mach number for the plain flap of the present report is given in figure 3 for several moderate lift coefficients. For comparison, the variation of the lateral-control-effectiveness parameter with Mach number for a 20-percent-chord plain flap on a 19-percent-thick modified NACA 65-series airfoil is also shown in figure 3. The curve for the latter airfoil and flap was obtained from figure 43 of reference 3. For the present report, values of $\Delta\alpha_o/\Delta\delta_f$ were taken as the absolute value of the average slopes of the curve of section angle of attack versus flap deflection over a range of flap deflections from -6° to 6°, for a constant section lift coefficient.

A graph (fig. 4) has been prepared which illustrates the respective variations with Mach number of increments in section lift coefficient with flap deflection for the plain flap and for the dive-recovery flap, and of decrements in section lift coefficient with projection for a spoiler. From the high-speed investigation (two-dimensional) of a spoiler located at several positions on the upper surface of the NACA 65-210 airfoil section, it appeared that the 50-percent-chord location was the most suitable investigated. Decrements of lift coefficient for various spoiler projections at this location are shown in figure 4 for an airfoil angle of attack corresponding to a lift coefficient of 0.2 at zero spoiler projection. Similarly, the increments of lift coefficient for several dive-recovery flap deflections are also shown in figure 4 for a corresponding airfoil angle of attack and for the dive-recovery flap located at the 50-percent-chord position. The high-speed investigation (two-dimensional) of dive-recovery flaps indicated that, of three flap locations on the lower surface of the NACA 65-210 airfoil, the 50-percent-chord position was also the most suitable location.

The changes in section drag and pitching-moment coefficients corresponding to the increments (or decrements) of lift coefficient shown in figure 4 are presented in figures 5 and 6, respectively, for the same three lift-control devices.

The dotted portions of certain curves appearing in figures 1 and 2, and of the curve of figure 3 for the 19-percent-thick airfoil are used to indicate that some uncertainty exists regarding the validity of these data obtained in the vicinity of the wind-tunnel choking Mach number (0.9 at zero angle of attack for the NACA 65-210 airfoil model, and approximately 0.74 at zero angle of attack for the 19-percent-thick airfoil model).

DISCUSSION

A desirable lift-control device for use on aircraft wings or tail surfaces is one which has uniform effectiveness throughout the range of Mach numbers at which the device is expected to be employed. Furthermore, if an airplane is to maintain controlled flight at Mach numbers above those for lift divergence of the wing (which are generally lower than those for lift divergence of the tail), it must be possible to compensate for the lift deficiency of the wing at those Mach numbers. These two particulars are considered in the succeeding discussion both in regard to the plain flap of the present analysis and in regard to the comparison that follows. The two-dimensional data presented herein can indicate, in general, the aerodynamic effects on an airplane wing or tail resulting from the use of one of the lift-control devices. It should be remembered, however, that several other factors which are not considered in this analysis, such as the differences in the aerodynamic characteristics of the tail and wing, the downwash at the tail, and the elevator hinge-moment characteristics, may greatly affect the over-all longitudinal-stability and -control characteristics of an airplane in flight, especially at high speeds.

Effectiveness of the Plain Flap as a Lift-Producing Device

The increments of section lift coefficient shown in figures 1 and 2, which indicate the effectiveness of the flap as a lift-producing device, show that the effectiveness increases somewhat with increase in Mach number reaching a maximum at a Mach number apparently depending on the magnitude of the flap deflection and the airfoil angle of attack. The Mach numbers for which the increments of lift coefficient are greatest correspond approximately, in most cases, to the airfoil lift-divergence Mach numbers given in figure 8 of reference 4. In the range of Mach numbers from those at which the maximum increments occur to 0.875 Mach number the effectiveness decreases in varying degree. The minimum effectiveness indicated, however, is never less than 50 percent of that at low speeds. Although the data of figures 1 and 2 indicate appreciable variations in the effectiveness of the plain flap for Mach numbers between 0.3 and 0.875, it is believed that these variations will not too seriously limit the application of this control device on a 10-percent-thick rigid airfoil in the said Mach number range.

Figures 1 and 2 further indicate the plain flap to be capable of providing substantial increments of lift coefficient for small flap deflections at Mach numbers above those for airfoil lift divergence. The plain flap, then, used either on a thin rigid airplane wing or tail remains effective as a lift-producing device at speeds greater than those corresponding to the wing or tail lift divergence, respectively.

Effectiveness of the Plain Flap for Lateral Control

The lift-control characteristics of a plain flap at high speeds are of further significance from the standpoint of the lateral control of an airplane. The lateral-control effectiveness of the plain flap of the present report can be evaluated from the data of figure 3 which show the variation with Mach number of the section lateral-control-effectiveness parameter $\Delta\alpha_o/\Delta\delta_f$. For any given airplane the magnitude of the parameter $pb/2V$ (helix angle generated by the wing tip of an airplane in roll) is directly proportional to the airfoil-section lateral-control parameter $\Delta\alpha_o/\Delta\delta_f$ (assuming a rigid airplane wing). A study of the variations of $\Delta\alpha_o/\Delta\delta_f$ with Mach number will, accordingly, correspond to a study of the variations of $pb/2V$ of an airplane employing the airfoil and lift-control device. Furthermore, whatever decrease in the values of $pb/2V$ with increase in Mach number can be allowed for an airplane, consistent with the maintenance of adequate lateral control, can also be allowed for the airfoil-section parameter $\Delta\alpha_o/\Delta\delta_f$.

The data of figure 3 for the NACA 65-210 airfoil with a plain flap show an appreciable variation in lateral-control effectiveness over a range of moderate lift coefficients at high Mach numbers. The only marked decreases in effectiveness, however, appear to begin at Mach numbers near 0.83 for low lift coefficients. The largest decrease in effectiveness, for Mach numbers up to 0.875, is indicated for zero lift coefficient where the effectiveness has reduced to a value which is approximately 50 percent of that shown for low speeds. In a Navy Department specification for the stability and control characteristics of airplanes (reference 5), no reduction in the minimum allowable value of $pb/2V$ for adequate lateral control is permitted for indicated airspeeds up to 300 miles per hour, but a two-thirds reduction is permitted for an increase in indicated airspeed from 300 to 500 miles per hour. At an altitude of 10,000 feet (an altitude specified in reference 5 at which compliance with these lateral-control requirements are to be demonstrated by the airplane in flight) indicated airspeeds of 300 and 500 miles per hour correspond, respectively, to approximately 0.5 and 0.8 Mach numbers. The plain trailing-edge flap applied to a rigid wing appears, then, to exhibit adequate lateral-control characteristics up to Mach numbers as high as 0.875.

A comparison of the curves of figure 3 for the two airfoils employing 20-percent-chord flaps shows that the effectiveness exhibited by the flap on the 19-percent-thick airfoil at high speeds is quite different from that for the 10-percent-thick airfoil. The curve for the 19-percent-thick airfoil shows a marked decrease in the effectiveness of the flap at a Mach number near 0.70 which is approximately 0.13 Mach number less than that corresponding to the abrupt decrease in effectiveness of the flap on the 10-percent-thick airfoil at low lift coefficients. It can also be noted from the data of figure 3 that, while serious losses in the effectiveness of a flap on a 19-percent-thick airfoil can be expected above Mach numbers of the order of 0.7, no severe losses should be expected for a plain flap on a 10-percent-thick airfoil, especially for higher lift coefficients, up to Mach numbers approaching 0.875.

Comparison of the Lift-Control Effectiveness of a Spoiler, a Dive-Recovery Flap, and a Plain Flap

The relative merits of a spoiler, a dive-recovery flap, and a plain flap for providing lift control on an airfoil can be evaluated from the lift-coefficient data presented in figure 4. It can be seen readily from the data that the variations with Mach number of the lift-control effectiveness of the spoiler and the dive-recovery flap from a Mach number of 0.3 to 0.875 are considerably larger than the corresponding variations for the plain flap. Because of these large variations in effectiveness for the dive-recovery flap, and especially for the spoiler, an airplane control system employing either of these devices would tend to provide at high speeds too rapid airplane response to control movements if satisfactory low-speed control characteristics were maintained. For producing lift continuously throughout a wide range of Mach numbers, the plain trailing-edge flap, accordingly, appears to possess the most favorable characteristics.

For providing auxiliary lift at Mach numbers above those for airfoil lift divergence, the plain flap deflected in a positive sense and the dive-recovery flap are considered for positive increments of lift; whereas the plain flap deflected in a negative sense and the spoiler, on the other hand, are considered for negative increments of lift. The data of figure 4 show that each of these lift devices is capable of providing increments (or decrements) of lift coefficient in the range of Mach numbers between 0.75 and 0.875. (This range includes Mach numbers above those for lift divergence of the airfoil). These increments, however, vary differently for each lift device with changes in Mach number and decrease with increase in Mach number at the highest Mach numbers shown, except for the 10° deflection of the dive-recovery flap and for positive deflections of the plain flap. The plain flap appears to have no particular advantage over the dive-recovery flap for providing positive increments of lift at Mach numbers between 0.75 and 0.875 on a 10-percent-thick airfoil unless it be at the highest Mach numbers. At the Mach numbers near 0.875 the data for the plain flap show that the increments of lift coefficient for the larger flap deflections do not continue to decrease with increase in Mach number as the corresponding increments do for the dive-recovery flap.

The increments of drag coefficient corresponding to constant increments of lift coefficient, as shown in figure 5, are seen to be quite different for the three lift-control devices. The characteristics for the plain flap appear to be the most desirable, since the data indicate that the increments in drag accompanying a given increment in lift is the least for the plain flap at any Mach number from 0.3 to 0.875. Between 0.75 and 0.875 Mach numbers the increments in drag coefficient for constant increments of lift coefficient of the dive-recovery flap increase very rapidly with increase in Mach number. In the case where a lift-control device is used on an airplane wing as a purely emergency implement for aid in recovery from high-speed dives, a substantial increase in drag, such as noted for the dive-recovery flap, may be desirable in order to limit the diving speed of the airplane.

At constant increments of lift coefficient, the increments of pitching-moment coefficient presented in figure 6 do not vary a great deal with change in Mach number except, for the most part, at the highest Mach numbers. For negative increments of lift at Mach numbers between 0.3 and 0.875, the plain flap and the spoiler exhibit, in general, positive increments of pitching moment which tend to increase at the highest Mach numbers for the larger negative increments of lift. The pitching-moment increments for positive increments of lift are negative for the plain flap, and positive for the dive-recovery flap except for the larger increments of lift at high Mach numbers. The data show that the increments of pitching moment are always more positive for the dive-recovery flap than are the corresponding pitching-moment increments for the plain flap. In the range of Mach numbers from 0.75 to 0.875 the pitching-moment coefficients for the plain flap are always negative (not in the direction to oppose the diving tendency); whereas for the dive-recovery flap they appear to be either positive or negative, depending on the Mach number and the increment of lift coefficient. A negative increment of pitching moment accompanying the use of any lift-control device at high subsonic speeds should certainly be considered in the structural and aerodynamic design of an airplane tail.

The diving tendency of airplanes, resulting from the loss in wing lift at Mach numbers above those for lift divergence of the wing, is generally accompanied by an increase in longitudinal stability and by trim changes. As a consequence, the control forces of some airplanes in high-speed dives increase to such an extent that it has been found necessary to employ dive-recovery flaps as an emergency device to aid the pilot in pulling out from the dives. On the other hand, pilots of some of the more recent high-speed aircraft have effected recovery from high-speed dives without recourse to emergency devices. In emergency applications the dive-recovery flaps are advantageous in that they increase the wing lift for airplane trim by providing an increment of lift together with a favorable pull-out moment. Since the data of figure 6 for the dive-recovery flap show that the pitching-moment increment is not always positive, it would appear that the use of these flaps on an airplane wing may not always provide favorable pitching moments for dive recovery as the Mach number or increment of lift is increased. (The data of reference 2 show that the dive-recovery flap located on the airfoil as far forward as the 30-percent-chord position also provides negative increments of pitching moment at high subsonic Mach numbers, except when the flap has a small chord ratio.)

If an airplane is to be controlled in flight, other than in dives, at Mach numbers above those for lift divergence of the wing, the use of dive-recovery flaps at these Mach numbers to provide auxiliary lift on the wing may be limited by the large increase in drag. The choice of a lift-control device for such operation should also depend upon a consideration of other factors such as the increments of pitching moment accompanying the use of the device, and the structural and high-speed aerodynamic characteristics of the airplane which is to employ the device.

CONCLUSIONS

The analysis of the lift-control characteristics of a 20-percent-chord plain trailing-edge flap on the NACA 65-210 airfoil section and a comparison of the effectiveness of this device with that of both the spoiler and the dive-recovery flap indicate the following:

1. At Mach numbers as high as 0.875, the plain flap on the 10-percent-thick airfoil retains at least 50 percent of its low-speed lift-control effectiveness, and is sufficiently effective in lateral control, assuming a rigid wing, to provide adequate airplane rolling characteristics.

2. As compared to the spoiler and the dive-recovery flap, the plain trailing-edge flap would appear to afford the most favorable characteristics as a device for controlling lift continuously throughout a range of Mach numbers from 0.3 to 0.875.

3. An airplane employing thin wings which is to be controlled in flight, other than in dives, at Mach numbers above those for lift divergence of the wing may use either a plain flap or a dive-recovery flap at these Mach numbers to provide auxiliary lift on the wing. It should be remembered, however, that the choice of a device for this use should include the consideration of other factors such as the increments of drag and pitching moment accompanying the use of the device, and the structural and high-speed aerodynamic characteristics of the airplane for which the choice is to be made.

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FIGURE LEGENDS

Figure 1.– Variation of the increment of section lift coefficient with flap deflection at various Mach numbers for several angles of attack of the NACA 65-210 airfoil with a 0.20-chord flap.

Figure 1.– Concluded. NACA 65-210 airfoil with a 0.20-chord plain flap.

Figure 2.– Variation of the increment of section lift coefficient with Mach number for various flap deflections and angles of attack of the NACA 65-210 airfoil with a 0.20-chord plain flap.

Figure 2.– Concluded. NACA 65-210 airfoil with a 0.20-chord plain flap.

Figure 3.– Comparison of the lateral-control effectiveness at various Mach numbers for the NACA 65-210 and 19-percent thick 65-series airfoils with 20-percent-chord plain flaps.

Figure 4.– Comparison of the lift-control characteristics of a spoiler, a dive-recovery flap, and a plain flap on the NACA 65-210 airfoil section at an angle of attack corresponding to a lift coefficient of 0.2 for zero deflection of the control device.

Figure 5.– Comparison of the increments of section drag coefficient corresponding to constant values of increment in lift coefficient given by a spoiler, a dive-recovery flap, and a plain flap on the NACA 65-210 airfoil section at an angle of attack corresponding to a lift coefficient of 0.2 for zero deflection of the control device.

Figure 6.– Comparison of the increments of section moment coefficient corresponding to constant values of increment in lift coefficient given by a spoiler, a dive-recovery flap, and a plain flap on the NACA 65-210 airfoil section at an angle of attack corresponding to a lift coefficient of 0.2 for zero deflection of the control device.

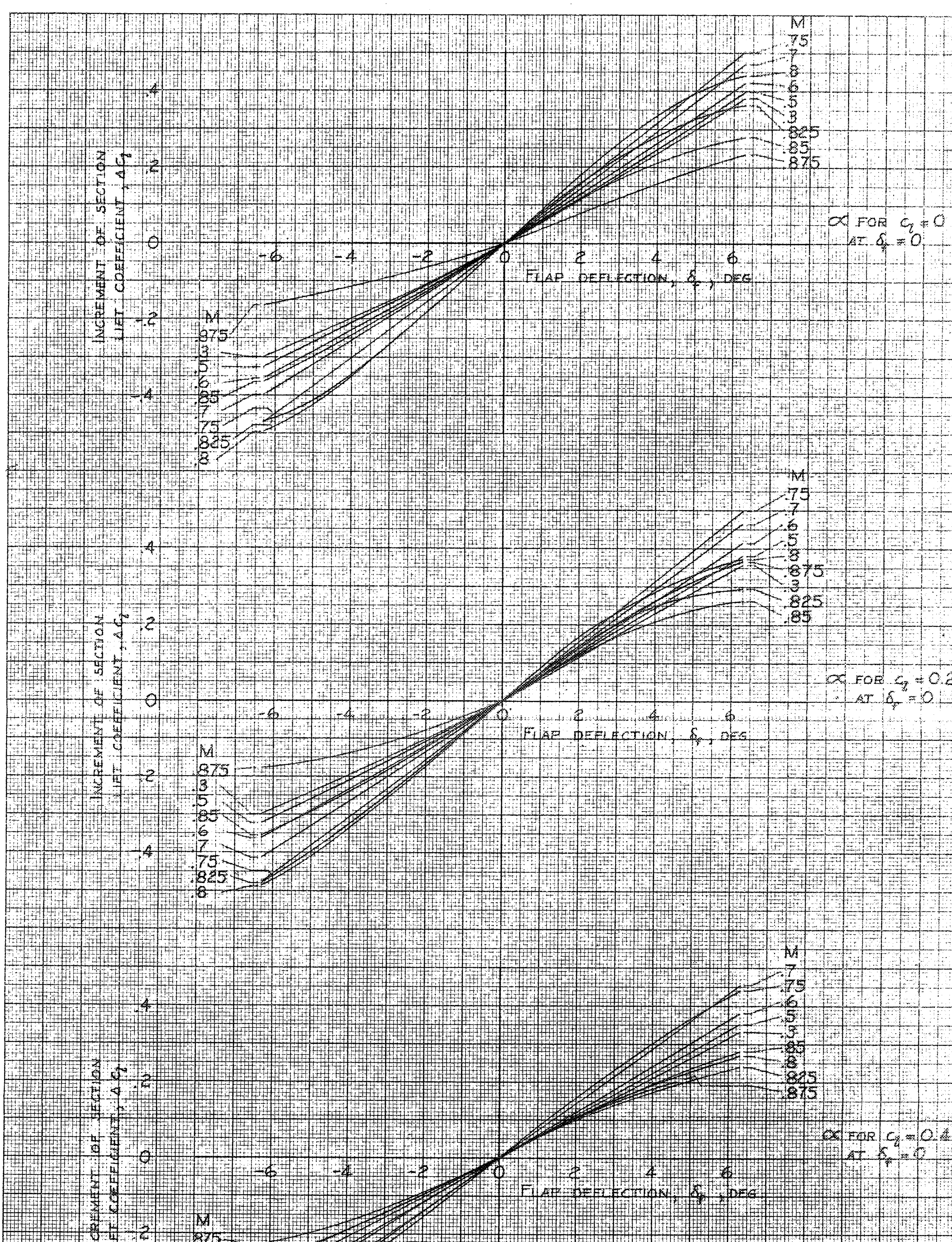
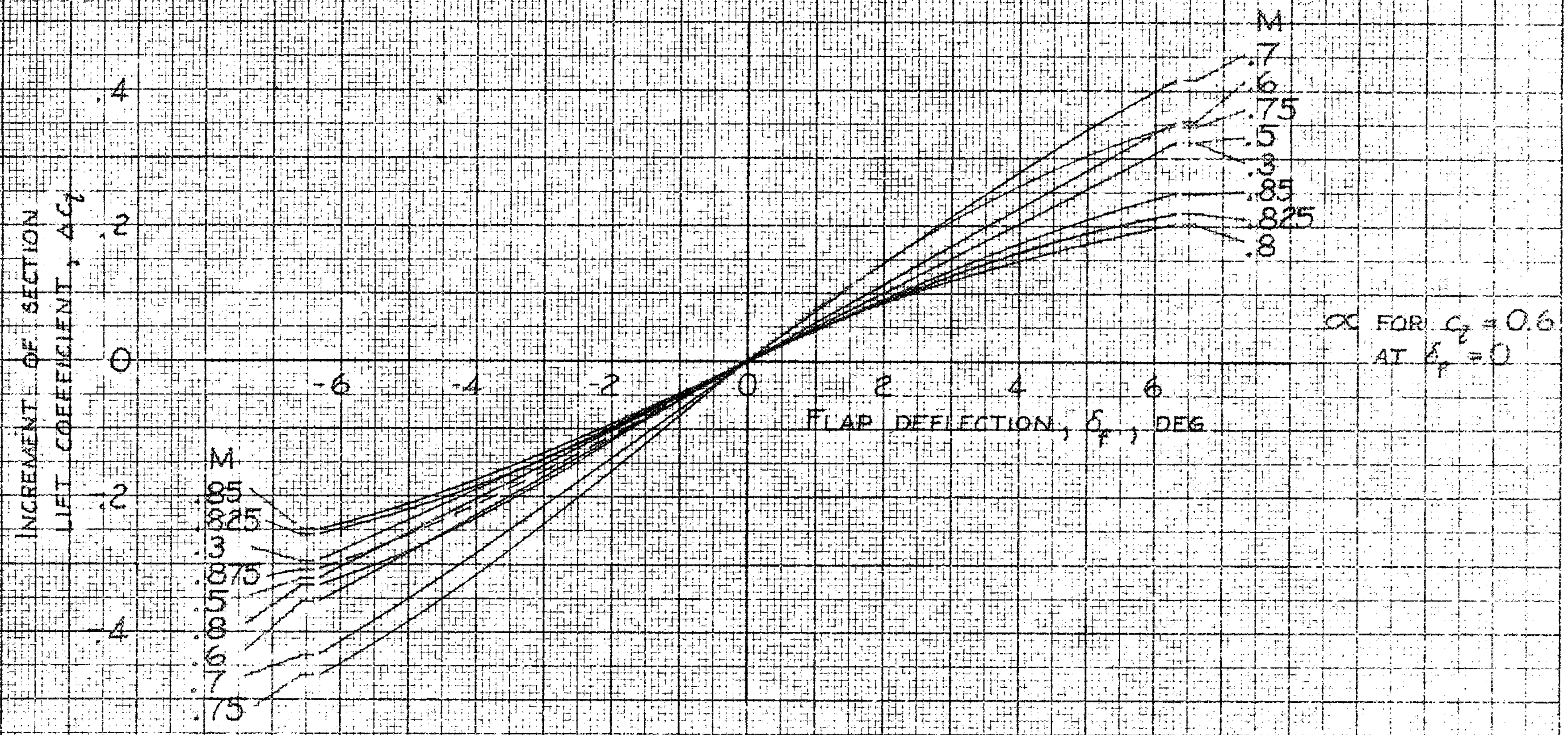


Figure 1.– Variation of the increment of section lift coefficient with flap deflection at various Mach numbers for several angles of attack of the NACA 65-210 airfoil with a 0.20-chord flap.



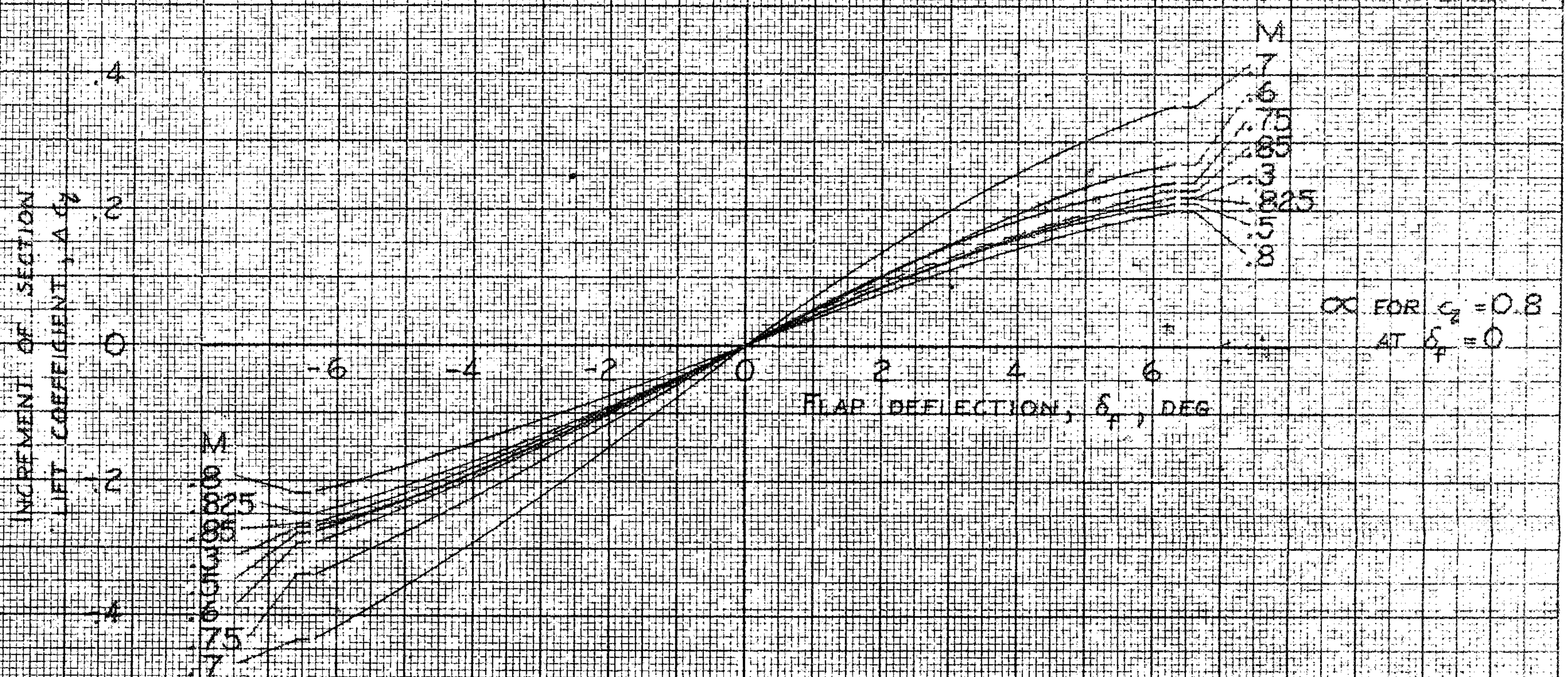


FIGURE 1. - CONCLUDED. NACA 65-210 AIRFOIL WITH A 0.20-CHORD PLAIN FLAP.

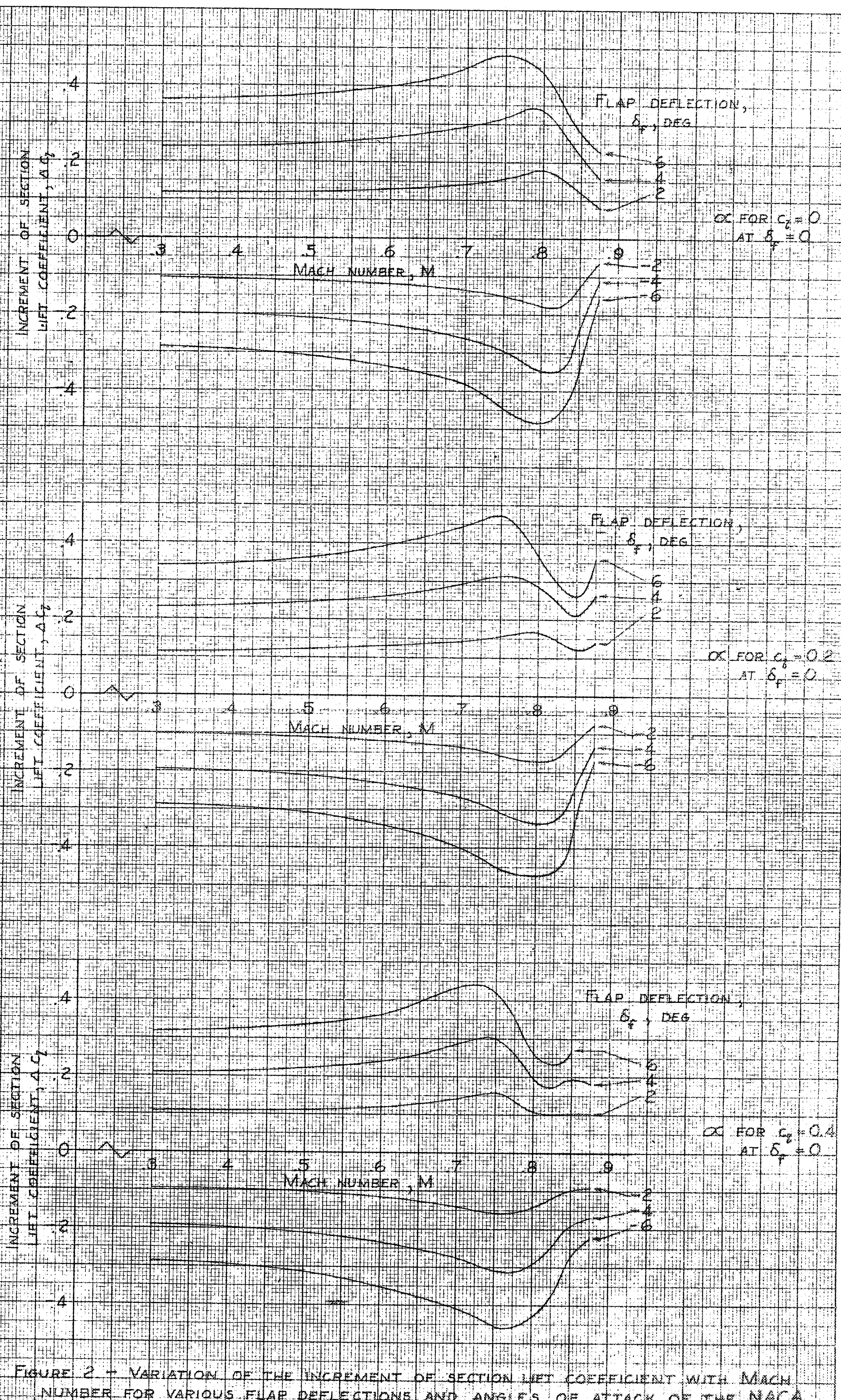
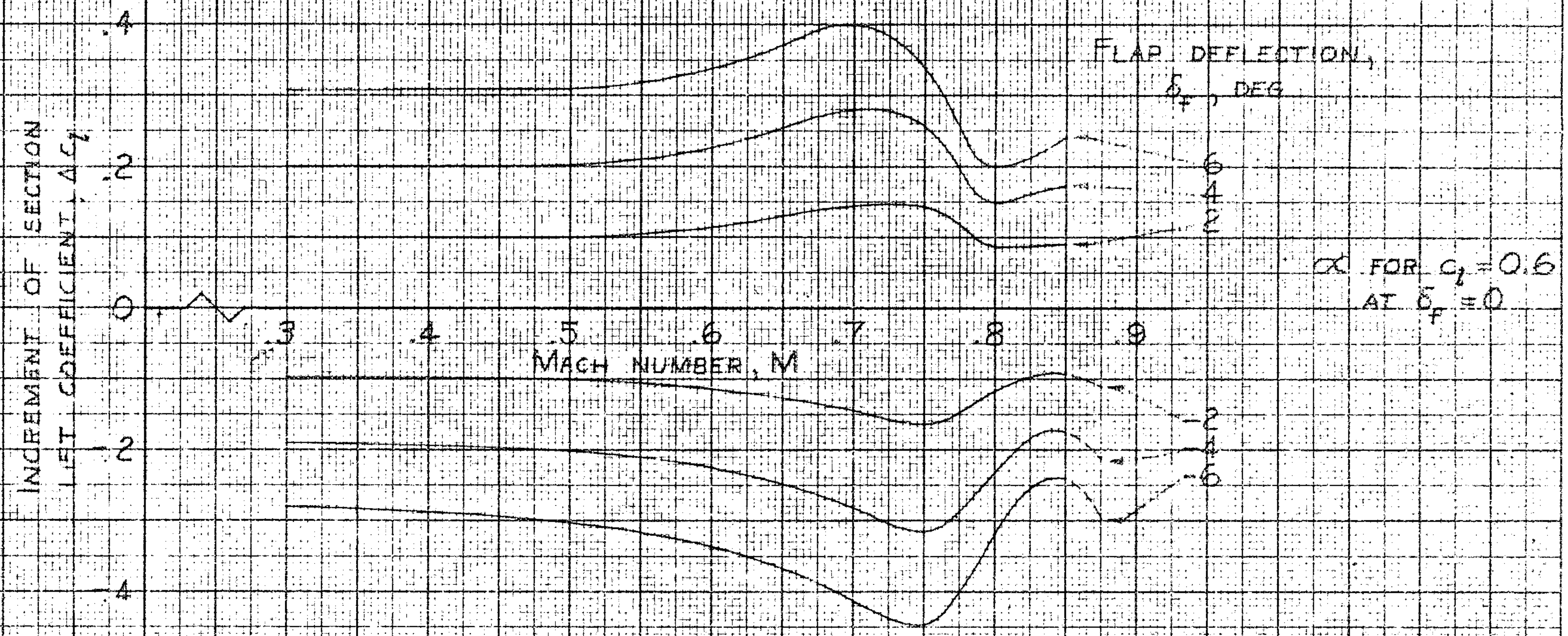


Figure 2 – Variation of the increment of section lift coefficient with Mach number for various flap deflections and angles of attack of the NACA 65-210 airfoil with a 0.20-chord plain flap.



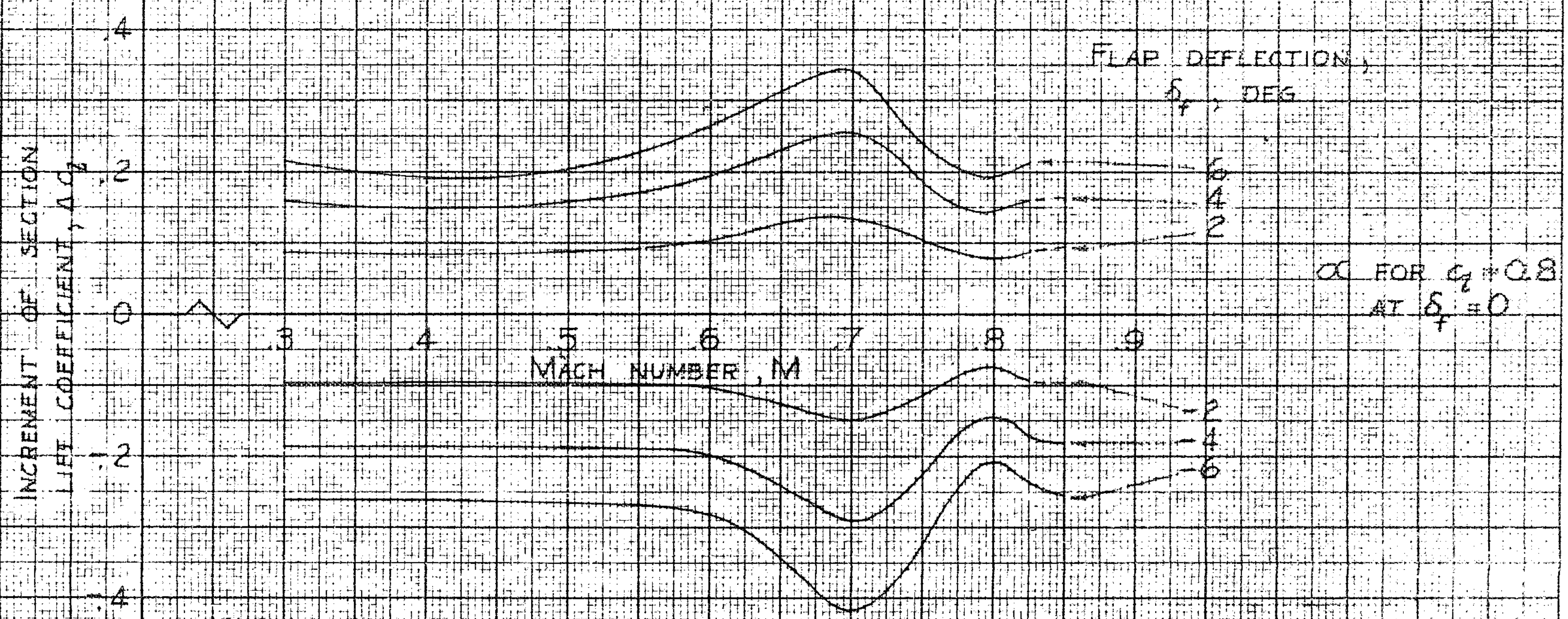


Figure 2 – Concluded. NACA 65-210 airfoil with a 0.20-chord plain flap.

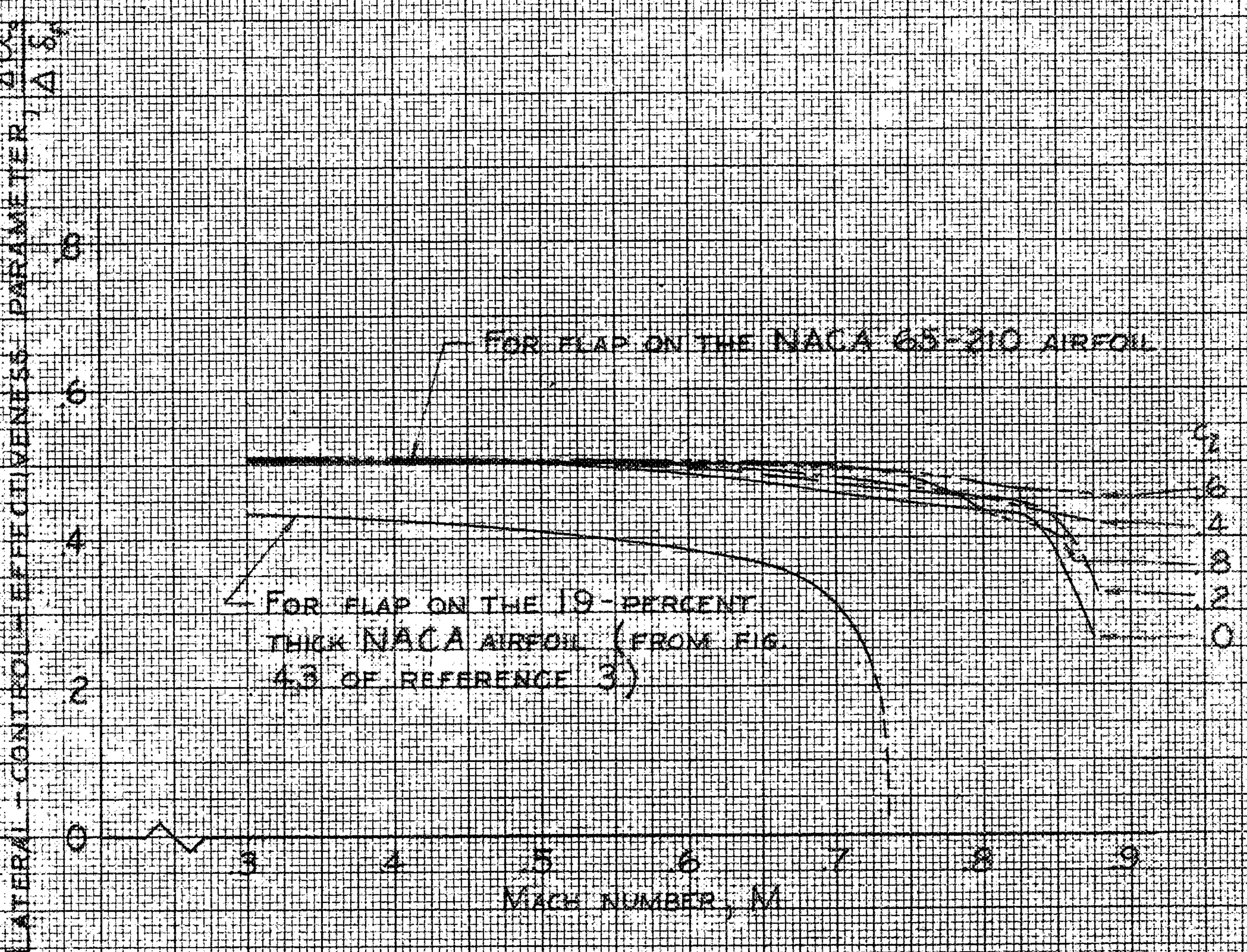


FIGURE 3. – COMPARISON OF THE LATERAL-CONTROL EFFECTIVENESS AT VARIOUS MACH NUMBERS FOR THE NACA 65-210 AND 19-PERCENT THICK 65-SERIES AIRFOILS WITH 20-PERCENT-CHORD PLAIN FLAPS.

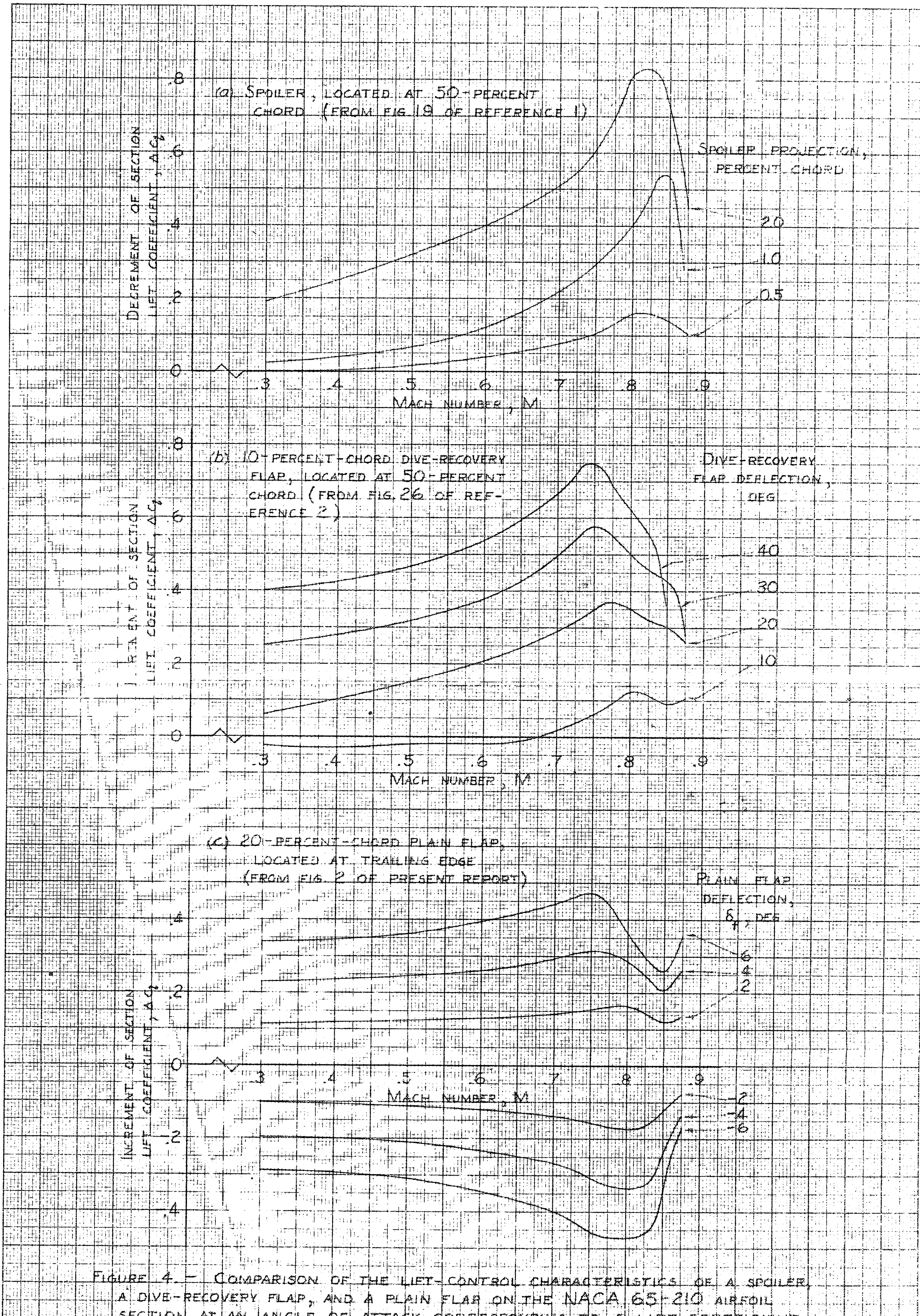


FIGURE 4.— COMPARISON OF THE LIFT-CONTROL CHARACTERISTICS OF A SPOILER, A DIVE-RECOVERY FLAP, AND A PLAIN FLAP ON THE NACA 65-210 AIRFOIL SECTION AT AN ANGLE OF ATTACK CORRESPONDING TO A LIFT COEFFICIENT OF 0.2 FOR ZERO DEFLECTION OF THE CONTROL DEVICE.

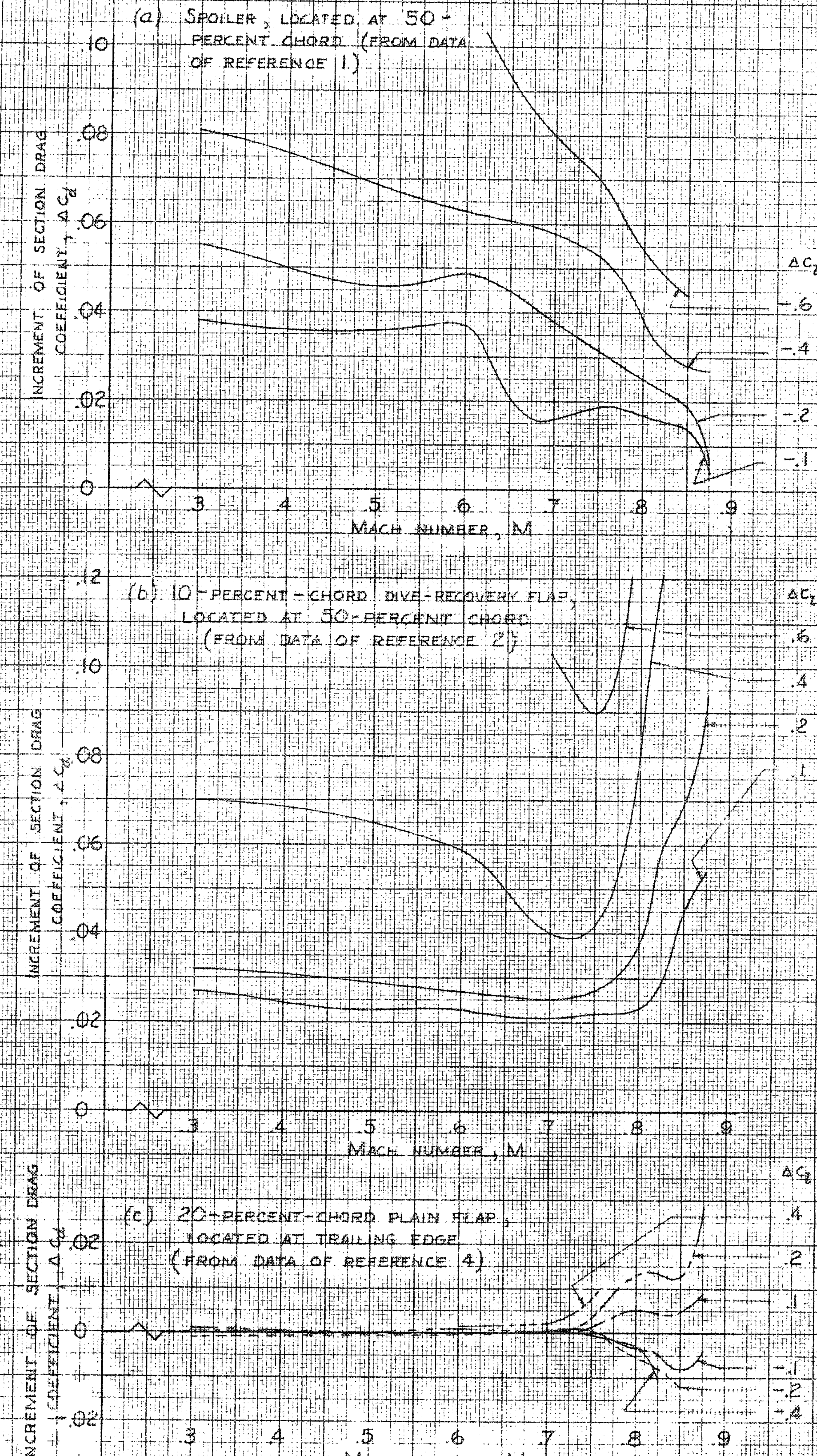


Figure 5. - Comparison of the increments of section drag coefficient corresponding to constant values of increment in lift coefficient given by a spoiler, a dive-recovery flap, and a plain flap on the NACA 65-210 airfoil section at an angle of attack corresponding to a lift coefficient of 0.2 for zero deflection of the control device.

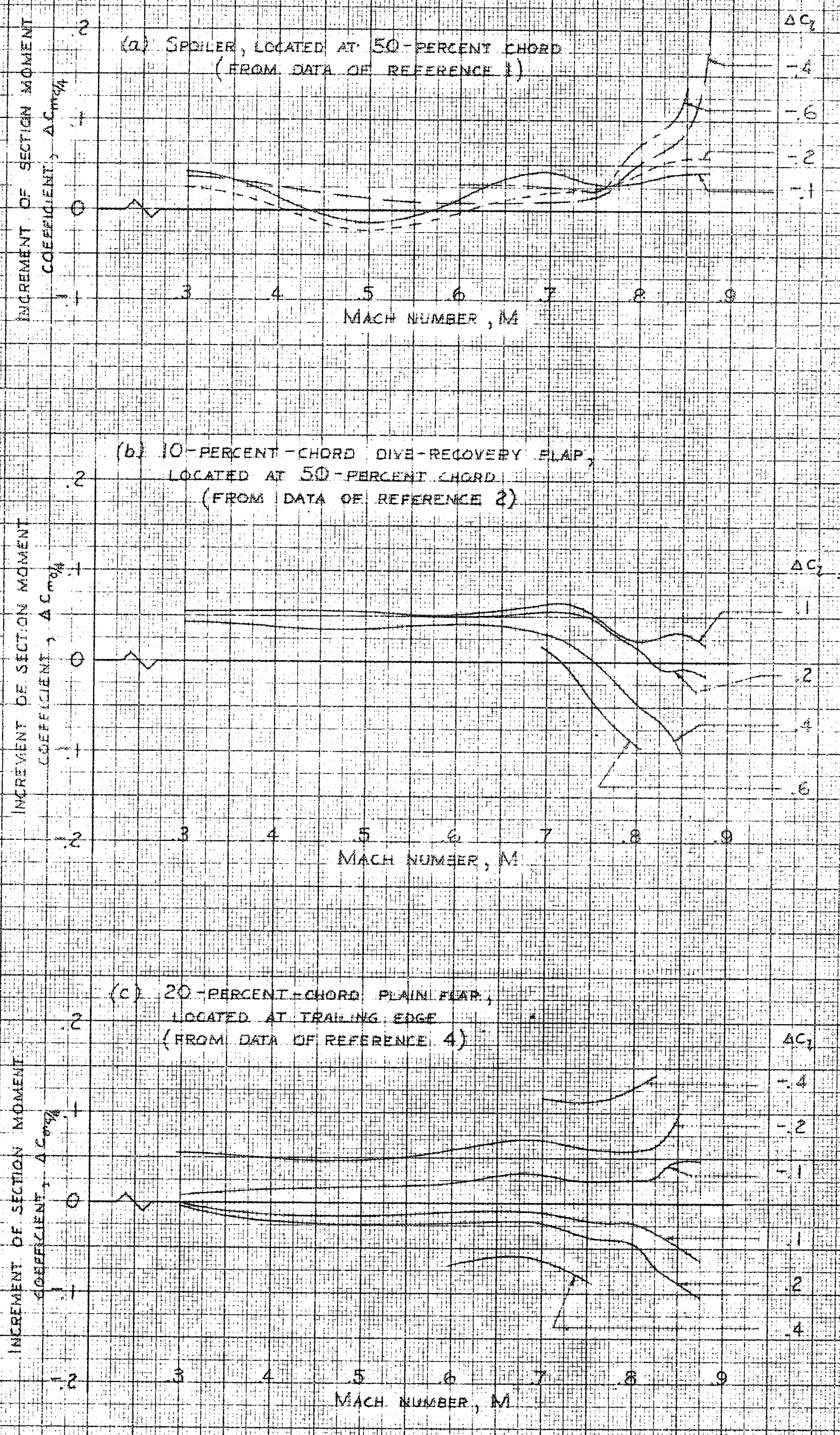


FIGURE 6.– COMPARISON OF THE INCREMENTS OF SECTION MOMENT COEFFICIENT CORRESPONDING TO CONSTANT VALUES OF INCREMENT IN LIFT COEFFICIENT GIVEN BY A SPOILER, A DIVE-RECOVERY FLAP, AND A PLAIN FLAP ON THE NACA 65-210 AIRFOIL SECTION AT AN ANGLE OF ATTACK CORRESPONDING TO A LIFT COEFFICIENT OF 0.2 FOR ZERO DEFLECTION OF THE CONTROL DEVICE.