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TECHNICAL NOTE

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TAKE-OFF DISTANCES OF A SUPERSONIC TRANSPORT CONFIGURATION AS AFFECTED BY AIRPLANE ROTATION DURING THE TAKE-OFF RUN

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SUMMARY

The take-off distances over a 35-foot obstacle have been determined for a supersonic transport configuration characterized by a low maximum lift coefficient at a high angle of attack and by high drag due to lift. These distances were determined analytically by means of an electronic digital computer. The effects of rotation speed, rotation angle, and rotation time were determined. A few configuration changes were made to determine the effects of thrust-weight ratio, wing loading, maximum lift coefficient, and induced drag on the take-off distance. The required runway lengths based on Special Civil Air Regulation No. SR-422B were determined for various values of rotation speed and compared with those based on full engine power.

Increasing or decreasing the rotation speed as much as 5 knots from the value at which the minimum take-off distance occurred increased the distance only slightly more than 1 percent for the configuration studied. Under-rotation by 1° to 1.5° increased the take-off distance by 9 to 15 percent. Increasing the time required for rotation from 3 to 5 seconds had a rather small effect on the take-off distance when the values of rotation speed were near the values which result in the shortest take-off distance. When the runway length is based on full engine power rather than on SR-422B, the rotation speed which results in the shortest required runway length is 10 knots lower and the runway length is 4.3 percent less.

INTRODUCTION

The take-off maneuver used in the operation of turbine-powered aircraft may be considered in three phases. First the airplane is accelerated on the ground while at a low-lift, low-drag attitude.

Next, as the velocity approaches that required for lift-off, the airplane is rotated to an angle at which the lift is sufficient to cause the airplane to lift off. Finally a transition is accomplished, with the flight-path angle increasing until a steady unaccelerated climb results at a desired or specified velocity.

The characteristics of some of the proposed supersonic transport configurations are such that rather large rotation angles (of the order of 12° to 14°) will be necessary in order to obtain a high enough lift coefficient for take-off. At these large angles the drag varies rapidly with angle of attack. This fact could cause the take-off distance to be very sensitive to the angle to which the airplane is rotated, to the time required to complete rotation, and to the rotation speed (horizontal speed at which rotation is initiated). Therefore, in planning future supersonic transport operation, it is important to determine the precision necessary for this maneuver.

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An analytical study has been made to determine the effect of rotation speed, rotation angle, and rotation time on the take-off distance of a supersonic transport configuration which will require a large rotation angle for take-off. The configuration considered herein has thrust and aerodynamic characteristics which fall within the range of many of the configurations being presently considered. In order to aid in the estimation of the effect of various configuration changes on the take-off distance, some data are presented for various values of thrust-weight ratio, wing loading, drag due to lift, and maximum usable lift coefficient. The take-off distances presented herein are based on full engine power, whereas the present regulations governing the operation of turbine-powered transport airplanes (Special Civil Air Regulation No. SR-422B) require the runway length to be based either on an engine failure occurring at a specified point during the ground run or on 115 percent of the full-power take-off distance, whichever distance is greater. The regulations which will govern the operation of the supersonic transport will very likely be somewhat different from the present regulations. There is a possibility that runway lengths based on full engine power will be allowed because of a reliable availability of afterburning, or duct burning, which would not normally be used near the ground but could be used in case of an emergency. The runway lengths based on SR-422B are presented and compared with the runway lengths based on full engine power.

SYMBOLS

C_D drag coefficient, $\frac{D}{qS}$

$C_{D,o}$ zero-lift drag coefficient

C_L lift coefficient, $\frac{L}{qS}$

$C_{L,MA}$ maximum usable lift coefficient

C_{L_α} variation of lift coefficient with angle of attack per degree, $\frac{\partial C_L}{\partial \alpha}$

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$\frac{\partial C_D}{\partial C_L{}^2}$ drag due to lift

D drag force, lb

g acceleration due to gravity, ft/sec^2

h altitude, ft

L lift force, lb

q dynamic pressure, $\frac{\rho V^2}{2}$, lb/sq ft

S wing area, sq ft

s distance along flight path, ft

T thrust, lb

Δt_R time required to rotate airplane from angle of attack of 0° to 13.9°, sec

V airplane forward velocity, knots

V_{mu} minimum unstick speed

V_R rotation speed (the speed at which the rotation maneuver is initiated), knots

V_1 critical-engine-failure speed, knots

V_{35} speed at 35-foot altitude

W airplane weight at take-off

W/S wing loading, lb/sq ft

α angle of attack or rotation angle, deg

α_{MA} maximum angle of attack used, deg

γ flight-path angle, radians

μ coefficient of rolling friction (assumed to be 0.02)

ρ density of air, slugs/cu ft

Subscript:

lo at lift-off

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ANALYSIS

The basic equations of motion used in this study are as follows:

$$\frac{dq}{ds} = \rho g \left(\frac{T}{W} - \mu + \frac{C_{L_\alpha} \alpha q \mu}{C_{L_{lo}} q_{lo}} - \frac{C_D q}{C_{L_{lo}} q_{lo}} - \gamma \right) \tag{1}$$

$$\frac{d\gamma}{ds} = \frac{\rho g}{2q} \left(\frac{C_{L_\alpha} \alpha q}{C_{L_{lo}} q_{lo}} + \frac{T}{W} \sin \alpha - 1 \right) \tag{2}$$

Only equation (1) (with $\gamma = 0$) was used during the ground run. After lift-off, which occurs when equation (2) becomes positive, the coefficient-of-friction terms were eliminated from equation (1) and the two equations were solved simultaneously by iteration. The IBM 650 electronic data processing machine was used for performing the calculations.

The parameters which define the basic configuration and configuration changes used in this study are given in table I. Several simplifications have been made, such as assuming a parabolic drag polar, assuming the lift-curve slope to be constant up to the maximum usable lift coefficient $C_{L,MA}$, and assuming zero lift at zero angle. The thrust-weight ratio was assumed to be constant throughout the take-off. The thrust axis is parallel to the wing reference axis.

Because of the lack of data available for estimating ground effects on these configurations, no attempt was made to include terms to account for ground effect. That is, the drag-due-to-lift values used represent effective values corresponding to higher basic free-air values. While the absolute values of take-off distance may be in error because of the exclusion of ground effect, the incremental differences which represent the effects of rotation speed, rotation time, rotation angle, and various configuration parameters are affected very little.

The operational characteristics and techniques assumed for each take-off are set forth as follows. At a given forward speed V_R, the rotation angle α was varied linearly with time from 0° to 13.9°. For most of the take-offs, the time required to rotate the airplane to 13.9° was 3 seconds, but 1, 2, 4, and 5 seconds were used as rotation times for a few take-offs. In cases where lift-off occurred before the maximum angle had been reached, the angle continued to increase to the maximum value after lift-off. After the angle had reached the maximum, it was held constant and the rest of the transition climb was made at a constant angle of attack to an altitude of 35 feet. Because of the short time involved in climbing to 35 feet, the full-landing-gear drag value was used. Even though the landing gear may have had time to retract partially, in no case would it have had time to retract fully. Except for the section of this paper which deals with SR-422B, all the take-off distances were computed on the assumption that all engines were operating at full power, and the distance was taken to be the horizontal distance from the start of the ground run to the point at which an altitude of 35 feet is reached. The data are all for standard conditions at sea level with no wind.

RESULTS AND DISCUSSION

Rotation Speed

The variation of take-off distance and the speed at a 35-foot altitude with rotation speed is given in figure 1. The minimum take-off distance is obtained when V_R is about 165 knots. If rotation were initiated at a speed 5 knots higher or 5 knots lower, the take-off distance would increase only 0.6 percent and 1.3 percent, respectively. Furthermore, if rotation were initiated at a speed 10 knots lower, the increase in take-off distance would be only about 3.7 percent, or 230 feet in this case.

The variation of take-off distance with rotation speed may be explained with the aid of figure 2. This figure shows the variation of angle of attack, airplane velocity, and altitude with horizontal distance for three take-offs covering a range of V_R values.

For the case represented by the circular symbols, the velocity has increased from 0 to 155 knots after the airplane has traveled 3,377 feet; at this point rotation is initiated, and the angle reaches the maximum value (13.9°) at a runway distance of 4,200 feet. For this angle the velocity is too low for the airplane to lift off. The airplane accelerates in this high-drag attitude, and when the velocity exceeds 174.9 knots, the vertical force component $L + T \sin \alpha$ becomes greater than the airplane weight, and the airplane lifts off the ground. The continued increase in velocity causes the lift force to increase and change the flight-path angle until an altitude of 35 feet is reached at a horizontal distance of 6,408 feet from the start. If the rotation speed is selected so that the maximum rotation angle θ_{MA} and an airplane velocity of 174.9 knots are reached simultaneously, as in the case represented by the square symbols, the airplane will lift off immediately upon completion of rotation and will avoid having to remain too long in the high-drag attitude. The horizontal distance traveled during the climb from lift-off to $h = 35$ feet is exactly the same for these two cases, since the angle of attack and velocity are the same at lift-off. The take-off resulting in the minimum distance is represented by the diamond symbols. Rotation was initiated after the airplane had traveled 3,870 feet and had reached a velocity of 165 knots. As a result of later rotation, the velocity at a given distance was higher than for the other two cases. The lift-off occurred farther down the runway than in the other two cases, but with slightly greater kinetic energy. Furthermore, the angle of attack was still increasing after lift-off, making the term $L + T \sin \alpha$ significantly greater than the weight. The combination of increasing the lift coefficient after lift-off and of being at a significantly higher dynamic pressure when the $C_{L,MA}$ value of 0.75 is reached results in a much sharper change in flight-path angle near lift-off for this case. Even though the ground-run distance to the lift-off point is greater for the take-off at $V_R = 165$ knots, the decrease in horizontal distance covered in climbing to $h = 35$ feet is sufficient to make the resulting take-off distance less than for the other cases; also, the airplane has greater energy at $h = 35$ feet for this case (see V_{35}, fig. 1). Increasing the value of V_R beyond 165 knots continues to decrease the horizontal distance covered during the climb to 35 feet, but the ground-run distance to lift-off increases enough to offset this decrease so that the resulting take-off distance increases as the rotation speed increases beyond 165 knots. However, the energy level at a 35-foot altitude continues to increase with increasing V_R up to the maximum V_R value investigated (fig. 1).

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Rotation Angle

It was shown in the previous section that the shortest take-off distance occurs when V_R is chosen so that the airplane lifts off when the angle α_{lo} is less than α_{MA}. Thus the rotation angle might be considered as the angle at lift-off, and the further increase in angle up to α_{MA} would be the angle-of-attack change used in the transition climb. For the purposes of this paper, however, "rotation" has been considered as one continuous maneuver and is defined as the change in angle of attack from 0° to α_{MA}. The rotation for the shortest take-off distance (figs. 1 and 2, $V_R = 165$ knots) was 95 percent complete at lift-off. Other data obtained during this study to show the effects of wing loading, induced drag, and thrust-weight ratio also bear out the fact that, with a maximum available lift coefficient of 0.75 to 0.95, the shortest take-off distance results when 93 to 95 percent of the available lift coefficient is used for lift-off and the rest is used to provide a lift increment to increase the flight-path angle during the start of the transition climb.

The effects of under-rotation are illustrated by figure 3, which presents the variation of angle of attack and altitude with horizontal distance for four take-offs with various values of α_{MA}. The value of $C_{L,MA}$ varies from 0.75 at $\alpha_{MA} = 13.9^\circ$ to 0.675 at $\alpha_{MA} = 12.5^\circ$ ($C_{L_\alpha} = 0.054$). The shortest take-off distance shown represents the basic configuration with $V_R = 165$ knots, just as previously shown in figure 2. The other three take-offs are for the same configuration and same V_R value, with α_{MA} limited to 13.4°, 13.0°, and 12.5°, to represent three cases of under-rotation. For the case of 0.5° under-rotation the lift-off occurs at the same angle (13.2°), distance, and velocity as for the take-off with full rotation; but an increment of only 0.2° further rotation after lift-off was used to increase the lift coefficient during the transition climb, whereas an increment of 0.7° was used when rotation was continued to 13.9°. The smaller lift increment which resulted when 0.5° under-rotation occurred caused the flight path to be longer, though the ground-run distances were equal, so that the take-off distance for this case increased 3.7 percent over that for the case of full rotation. For the cases of approximately 1° to 1.5° under-rotation the take-off is similar to that described in the previous section for the take-off with $V_R = 155$ knots. That is, the airplane has to stay in the high-drag attitude until the velocity reaches the higher value needed for lift-off with the lower lift coefficient. The increased take-off distance for the two values of α_{MA} below 13.2° is due not only to the decreased lift during the climb, but also to the increase in ground-run distance to the point of lift-off. The take-off distances for α_{MA} values of 13.0° and 12.5° indicate that under-rotation by 1° to 1.5° will increase the take-off distance for this configuration by 9 to 15 percent.

Rotation Time

The rotation time, as used in this paper, is the time required to rotate the airplane from $\alpha = 0^{\circ}$ to $\alpha = 13.9^{\circ}$. It is believed that rotation time will depend more on the time required for a pilot to execute a well-controlled rotation maneuver than on the maximum rotation capabilities of the airplane. A simulator study has recently been completed (ref. 1) in which several experienced test pilots made take-off runs with a simulator representing a configuration similar to the basic configuration used in this study. On the basis of these simulator tests it appears that rotation times from 3 to 5 seconds would be representative of a normal operating range. The variation of take-off distance with V_R is presented in figure 4 for rotation times Δt_R of 3, 4, and 5 seconds, and a limited amount of data is also presented for values of Δt_R of 1 and 2 seconds. The minimum take-off distance decreases only about 0.5 percent for each successive decrease of Δt_R from 5 to 4 to 3 seconds. The rotation speed that results in a minimum take-off distance increases from 155 to 165 knots as Δt_R decreases from 5 to 3 seconds.

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It would appear, on the basis of the previously mentioned simulator study, that V_R may be held within a reasonably narrow range near some desired value while Δt_R might vary by several seconds for different take-offs. Therefore, it would be of interest to examine the variation of take-off distance as Δt_R varies from 3 to 5 seconds for several values of V_R (fig. 5). For values of V_R of 155, 160, and 165 knots, it will be noted that the shortest take-off distance is given by the shortest rotation time (3 seconds) at the highest rotation speed (165 knots); however, when Δt_R is assumed to vary between 3 and 5 seconds, a V_R value of 160 knots will give a shorter take-off distance than a V_R value of either 155 or 165 knots for most of the Δt_R range.

Figures 4 and 5 indicate that for this configuration, variations in take-off distance for values of V_R between 155 and 165 knots and for Δt_R values between 3 and 5 seconds are rather small (3.5-percent total variation) and probably would be in the range of normal variations expected as a result of differences in pilot technique.

Comparison of Required Runway Lengths Based on SR-422B With Those Based on Full Engine Power

At the present time all turbine-powered transport-category airplanes for which a type certificate has been issued in the United States since August 29, 1959, are certified and operated according to SR-422B. These regulations are set forth in order to provide a suitable level of safety to cover engine failure, variations in pilot technique, variations in power due to temperature, and so forth. These regulations are too detailed to set forth here, but some of the essential points will be discussed briefly. The regulations limit the payload or aircraft take-off weight for each take-off according to the length of runway available. The runway required, or take-off distance, for each take-off is that distance in which the airplane can start from a standstill, experience an engine failure at some speed V_1, and continue the take-off to a height of 35 feet. The velocity V_1 is such that the distance required to continue the take-off to an altitude of 35 feet is equal to the distance required to bring the airplane to a stop. This method of determining the runway length required for a take-off is known as the "balanced field" concept. For the basic configuration the required runway length based on SR-422B, along with the required runway lengths based on full power, is presented in figure 6 as a function of V_R. The variation of V_1 with V_R is also shown. The thrust was reduced by 25 percent for the one-engine-out case (i.e., a four-engine airplane was assumed). In determining the stop distance it was assumed that the airplane traveled at V_1 for 2.6 seconds while engine failure was being recognized and before full braking was applied; then the airplane was decelerated with a steady braking deceleration equivalent to 0.2g. In order to insure a given safety margin under all conditions, a further requirement of SR-422B is, in essence, that the take-off distance shall be as determined for the case of an engine failure, or it shall be 115 percent of the full-power take-off, whichever is greater. This requirement determines the take-off distance based on SR-422B at the higher rotation speeds for the slower rotation rate $(\Delta t_R = 5$ seconds; see fig. 6).

The requirement in SR-422B which relates V_R to the minimum unstick speed V_{mu} would have little significance for a configuration of the type used in this study when the maximum lift coefficient available is determined by the maximum possible ground attitude, rather than by the stall.

If the regulations which govern the operation of the supersonic transport allow the required runway length to be based on full engine power, there will still be a necessity for some margin of safety.

As previously mentioned, a safety margin of 115 percent of the full-power take-off distance is now being used in some cases, in accordance with SR-422B, and this value (115 percent) was used in the determination of the runway lengths based on full power shown in figure 6.

For both values of rotation time (fig. 6) the value of V_R which results in the shortest runway length is decreased by 10 knots when runway length is based on full engine power. The minimum runway length, for each value of Δt_R, is about 4.3 percent less when based on full engine power than when based on SR-422B.

Effects of Configuration Changes

The effects of configuration changes are given in figures 7, 8, and 9, for configuration changes 1 to 9 (table I). The results show the variation of take-off distance with rotation speed for conditions of full power, standard sea-level atmosphere, and no wind.

Thrust-weight ratio.- The variation of take-off distance with rotation speed is given in figure 7 for thrust-weight ratios of 0.26, 0.30, 0.35, and 0.40. The effect of variations in rotation speed on the take-off distance becomes more pronounced as the thrust-weight ratio decreases.

Wing loading and maximum lift coefficient.- The effects of wing loading and maximum usable lift coefficient on take-off distance are shown in figure 8. The values of wing loading used are 85, 100, and 115 pounds per square foot, and the $C_{L,MA}$ values are 0.75, 0.85, and 0.95. The value of $C_{L,MA}$ is varied by changing the lift-curve slope and keeping α_{MA} constant. The value of $\partial C_D/\partial C_L^2$ was constant for all three lift-curve slopes. Increasing the wing loading increases the take-off distance and also increases the value of V_R at which the minimum distance occurs for a given wing loading. Increasing the maximum usable lift coefficient has the opposite effect.

Induced drag.- The effect of induced drag is presented in figure 9. Both the minimum take-off distance and the rotation speed which results in the minimum take-off distance increases slightly as the value of $\partial C_D/\partial C_L^2$ increases from 0.20 to 0.30. As would be expected, the variation of take-off distance with rotation speed is greater for the higher $\partial C_D/\partial C_L^2$ values than for the lower values.

CONCLUDING REMARKS

Take-off distances have been determined for a hypothetical supersonic transport configuration which is characterized by a low maximum lift coefficient occurring at a high angle of attack. The required runway lengths based both on Special Civil Air Regulation No. SR-422B and on full engine power were determined for this configuration. The following results have been indicated:

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1. Increasing or decreasing the rotation speed as much as 5 knots from the value at which the minimum take-off distance occurred increased the distance only slightly more than 1 percent for the configuration studied.

2. Under-rotation by 1° to 1.5° increased the take-off distance by as much as 9 to 15 percent.

3. Increasing the time required for rotation from 3 to 5 seconds had a rather small effect on the take-off distance when the values of rotation speed were near the values which result in the shortest take-off distance.

4. When the runway length is based on full engine power rather than on SR-422B, the rotation speed which results in the shortest required runway length is 10 knots lower and the runway length is 4.3 percent less.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Air Force Base, Va., September 8, 1961.

REFERENCE

1. Hall, Albert W., and Harris, Jack E.: A Simulator Study of the Effectiveness of a Pilot's Indicator Which Combined Angle of Attack and Rate of Change of Total Pressure as Applied to the Take-Off Rotation and Climbout of a Supersonic Transport. NASA TN D-948, 1961.

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TABLE I.- PARAMETERS DEFINING THE CONFIGURATION CHANGES

Configuration change	T/W	W/S	C_{L_α}	$C_{L,MA}$	$C_{D,o}$	$\frac{\partial C_D}{\partial {C_L}^2}$	Δt_R
Basic	0.35	85	0.054	0.75*	0.03	0.20	1, 2, 3, 4, and 5
1	.26	↓	↓	↓	↓	↓	3
2	.30	↓	↓	↓	↓	↓	↓
3	.40	↓	↓	↓	↓	↓	↓
4	.35	100	↓	↓	↓	↓	↓
5	↓	115	↓	↓	↓	↓	↓
6	↓	85	.061	.85	↓	↓	↓
7	↓	↓	.068	.95	↓	↓	↓
8	↓	↓	.054	.75	↓	.25	↓
9	↓	↓	↓	↓	↓	.30	↓

*For cases where α_{MA} was varied for the basic configuration, the values of $C_{L,MA}$ were based on $C_{L_\alpha} = 0.054$.

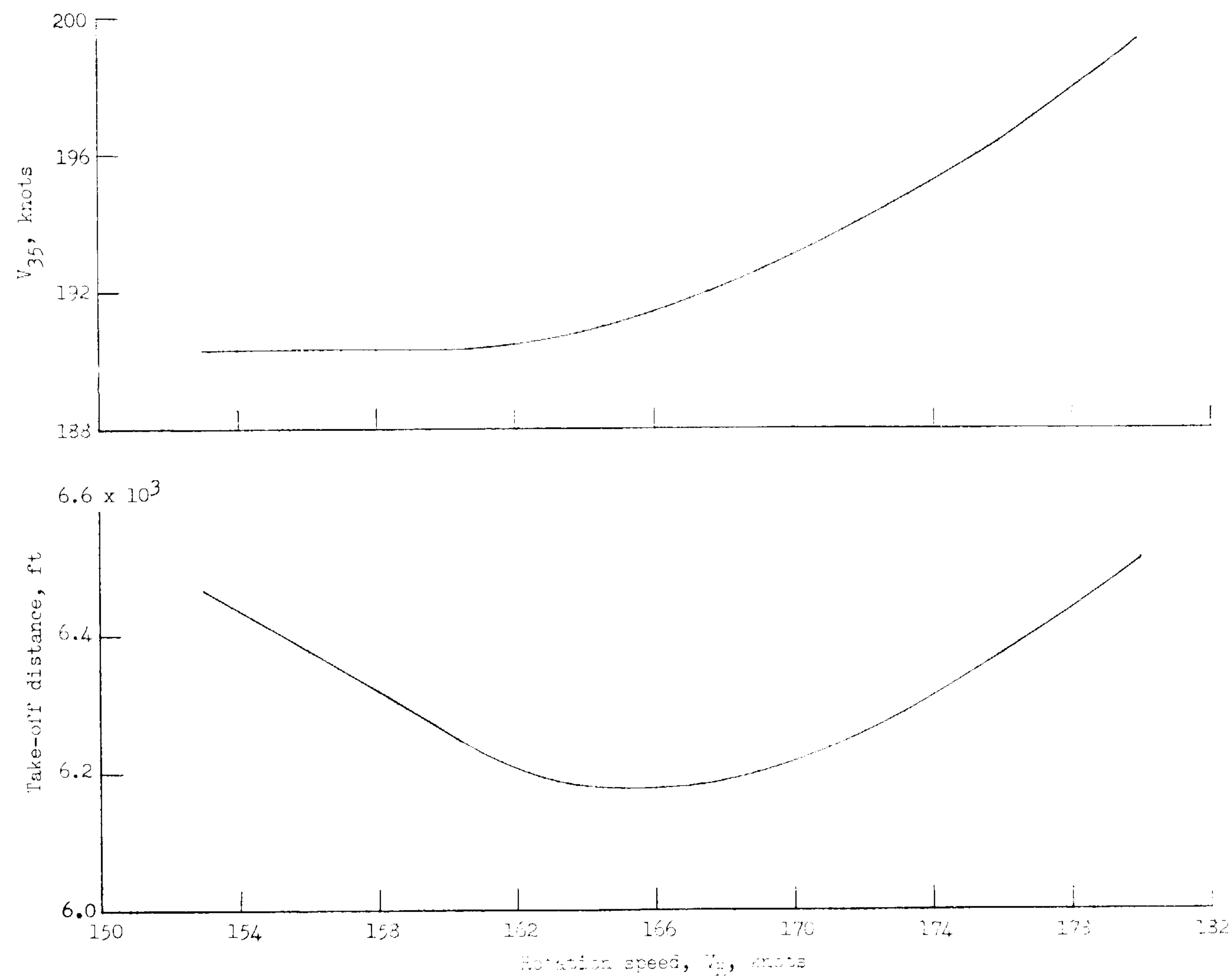

Figure 1.- Variation of take-off distance and V_{35} with rotation speed. $\Delta t_R = 3$ seconds.

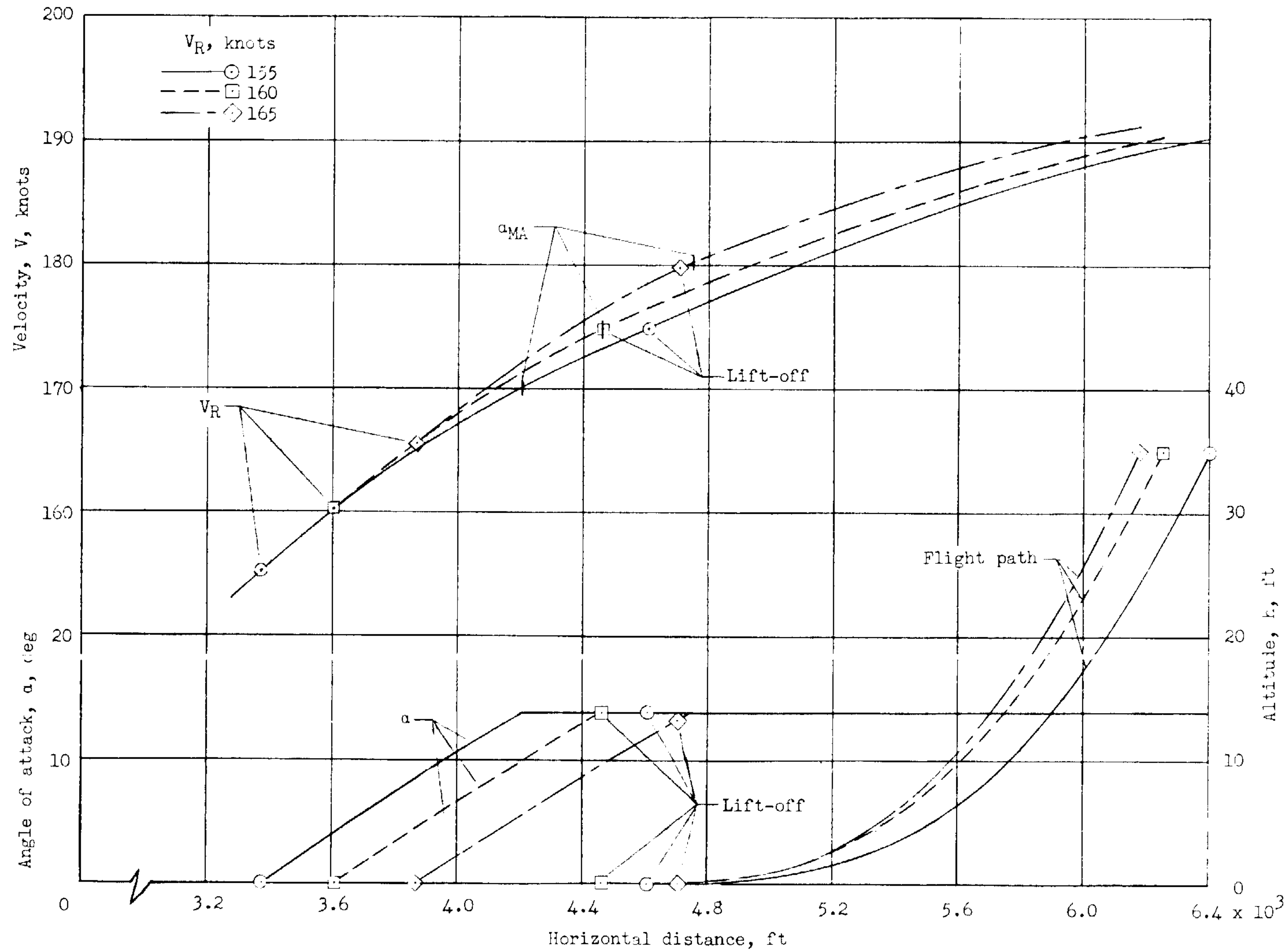

Figure 2.- Variation of angle of attack, altitude, and velocity with horizontal distance for three values of rotation speed. $\Delta t_R = 3$ seconds.

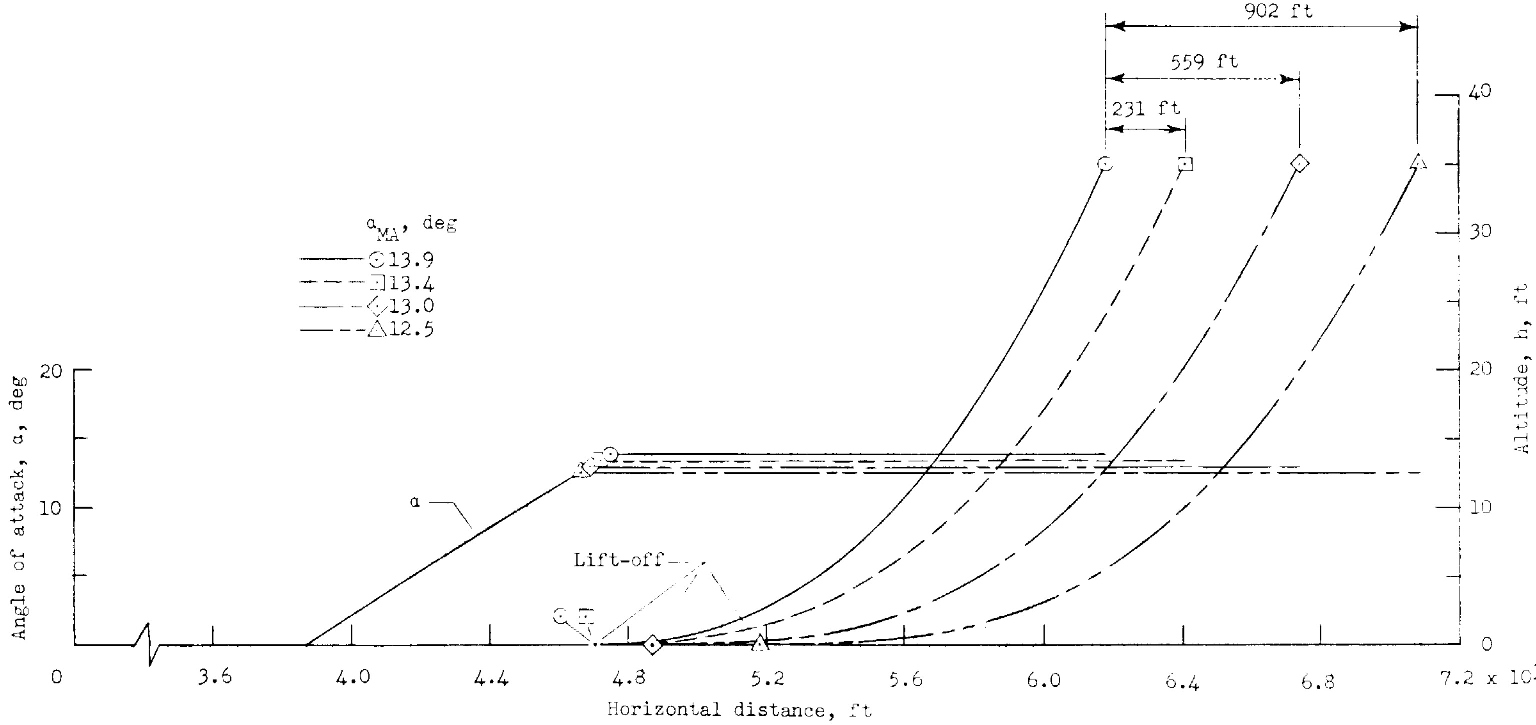

Figure 3.- Effects of under-rotation as illustrated by the variation of angle of attack and altitude with horizontal distance for four take-offs having different values of α_{MA}. V_R = 165 knots; rate of rotation is the same as the cases for Δt_R = 3 seconds.

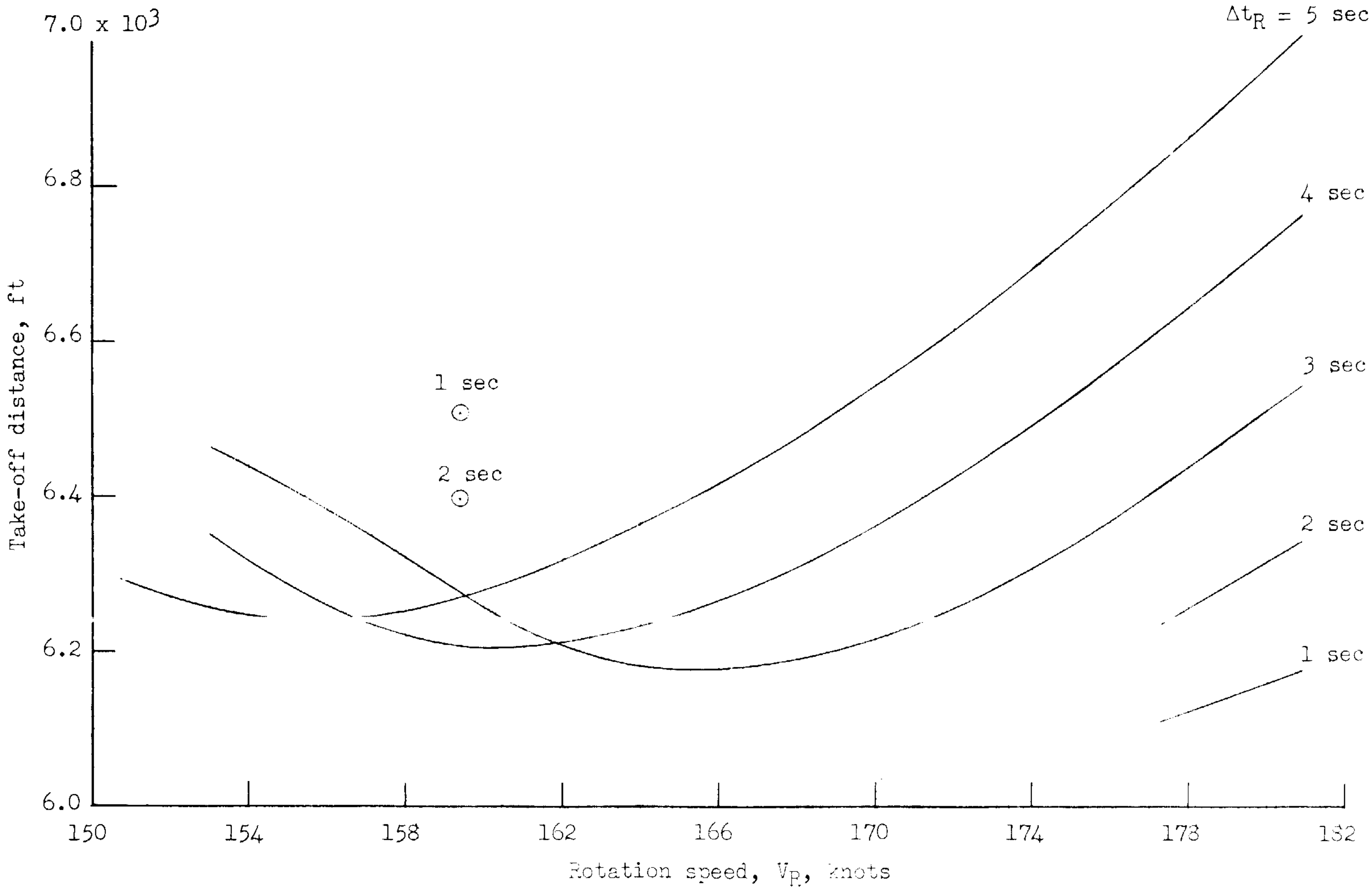

Figure 4.- Variation of take-off distance with rotation speed for rotation times of 1, 2, 3, 4, and 5 seconds.

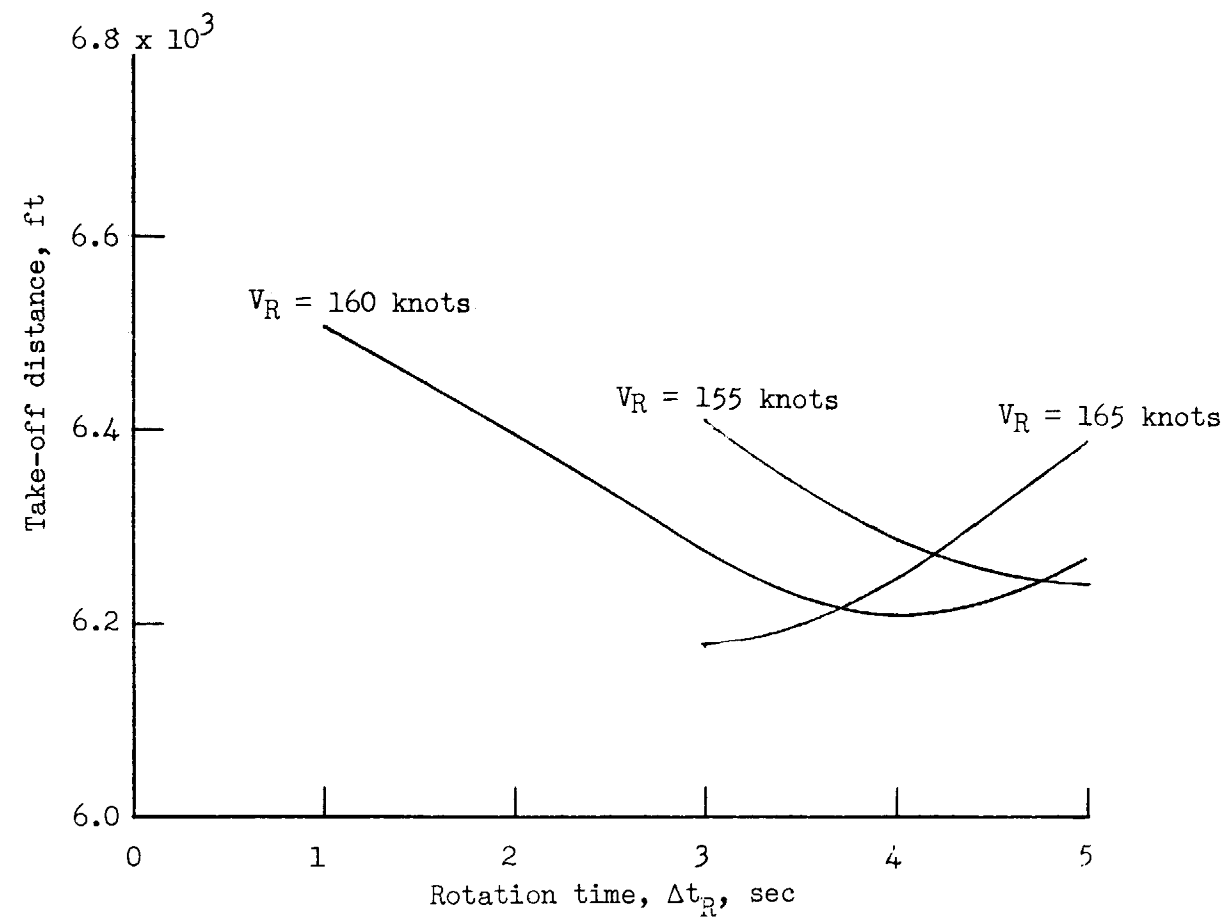

Figure 5.- Variation of take-off distance with rotation time for rotation speeds of 155, 160, and 165 knots.

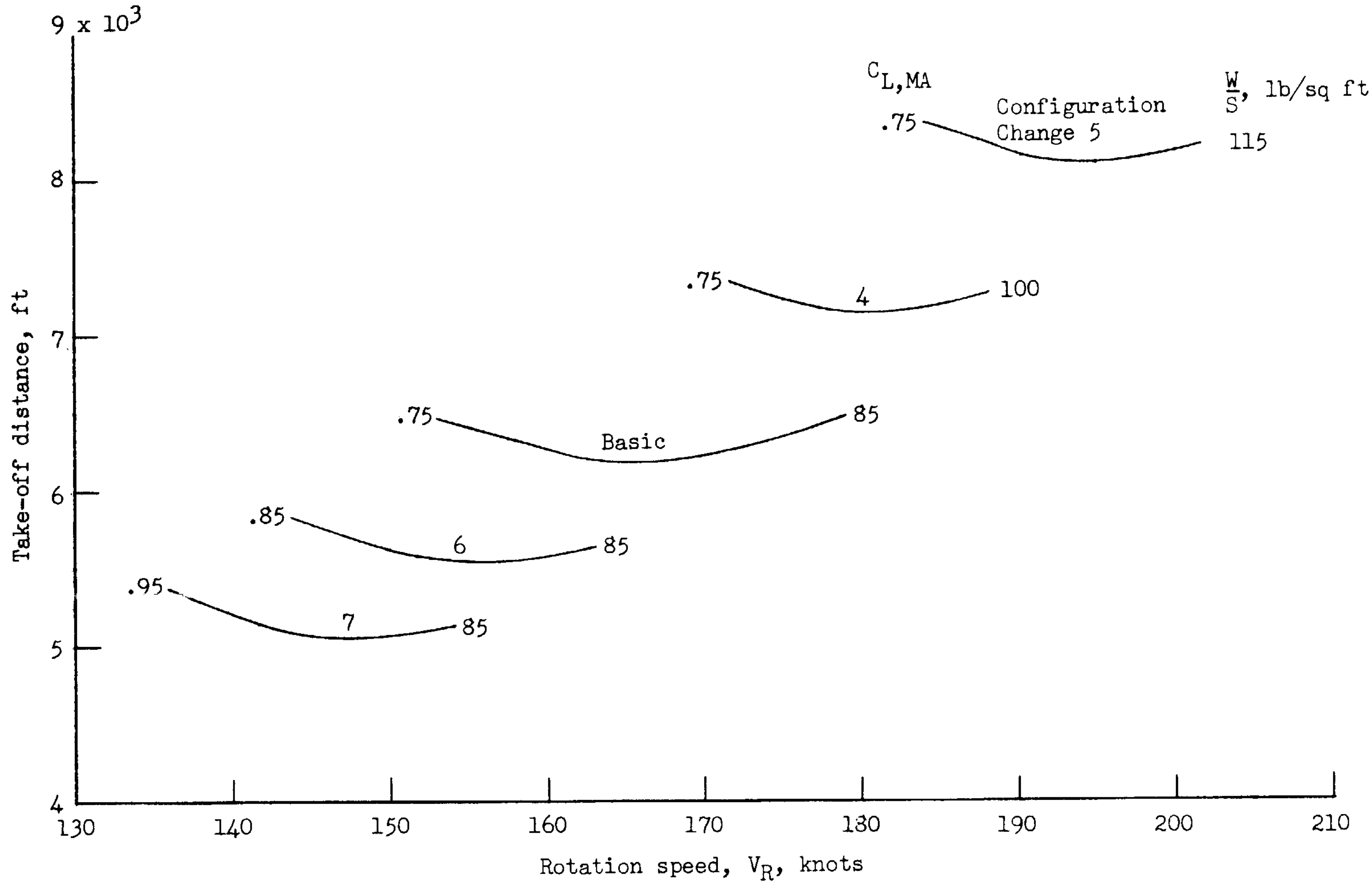

Figure 8.- Variation of take-off distance with rotation speed for various values of wing loading and maximum lift coefficient. $\Delta t_R = 3$ seconds.

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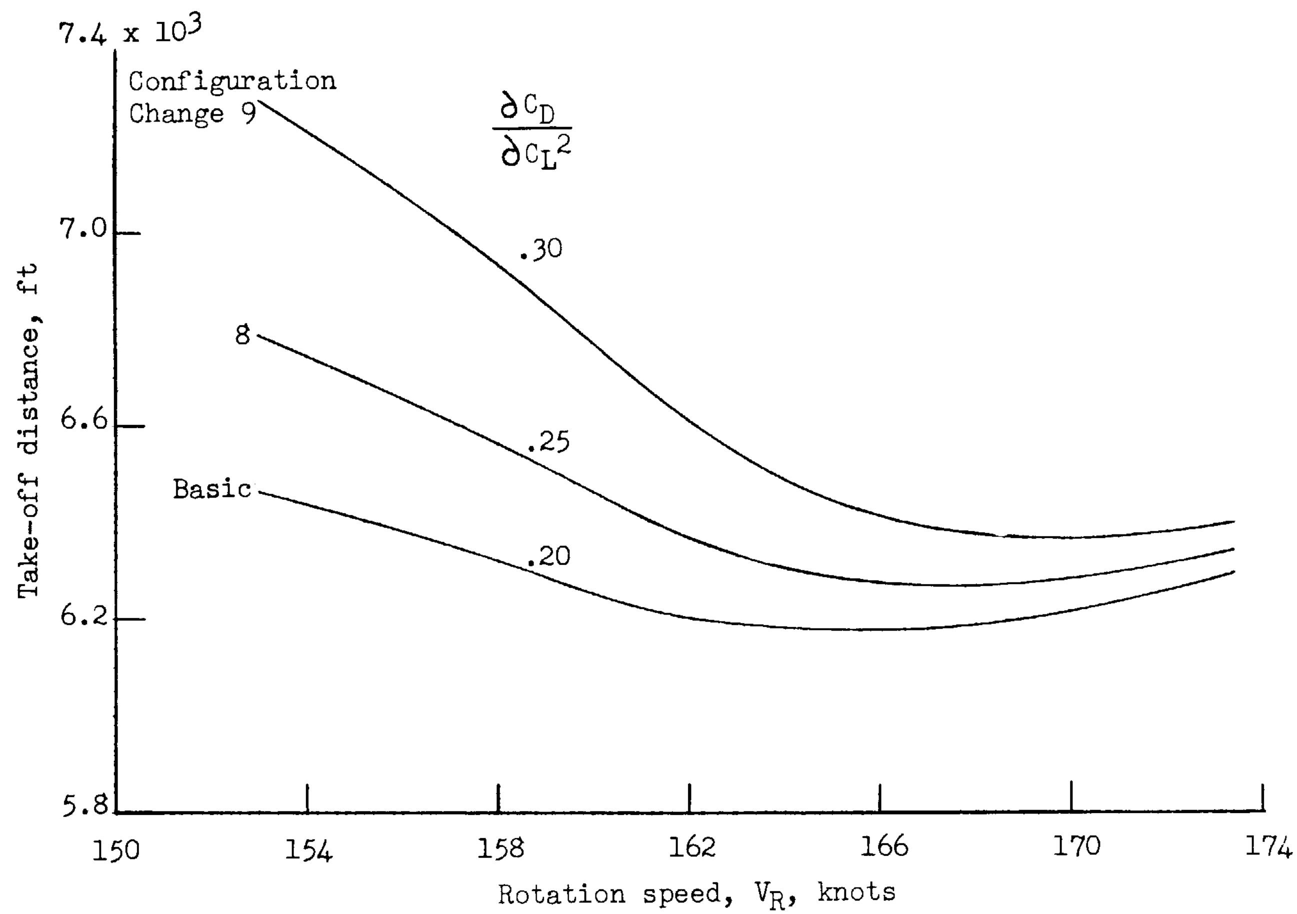

Figure 9.- Variation of take-off distance with rotation speed for various values of induced drag coefficient. $\Delta t_R = 3$ seconds.

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