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GROUND EFFECT FOR LIFTING ROTORS IN FORWARD FLIGHT

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SUMMARY

A theoretical analysis indicates that, for rotors, ground effect decreases rapidly with increases in either height above the ground or forward speed. The decrease with height above the ground in forward flight is greater than that in hovering. The major part of the decrease in ground effect with forward speed occurs at speeds less than 1.5 times the hovering mean induced velocity. Consequently, the total induced velocity at the rotor center increases rather than decreases when a helicopter gathers speed at low height above the ground.

INTRODUCTION

A lifting rotor incurs a favorable interference when operating very close to the ground. This ground effect has been studied extensively, both theoretically and experimentally (refs. 1, 2, and 3) for the case of hovering; however, little information is available for the case of forward flight.

Reference 4 calculates rotor ground effect in forward flight representing the rotor by means of a "directional" source. This representation of the rotor and its wake is, of course, extremely simple, and this very simplicity has occasionally raised questions as to the validity of the results.

A recent paper (ref. 5) presents studies of wind-tunnel jet-boundary interference in which the calculations are based upon a more representative rotor wake consisting of a skewed cylindrical vortex sheet. The interference for simple ground effect is readily obtained from the results of reference 5. The interference velocities so derived are presented herein. The calculated results are compared with those of reference 4 and the variation of ground effect with forward speed and height above the ground is studied in the light of the effect on the performance of a helicopter.

SYMBOLS

A_R rotor disk area, πR^2, sq ft

A_T cross-sectional area of wind-tunnel test section, 4BH, sq ft

B semiwidth of wind-tunnel test section, ft

C_T rotor-thrust coefficient, $\frac{\text{Thrust}}{\rho\pi R^2(\Omega R)^2}$

H semiheight of wind-tunnel test section, ft

K function defined by equation (1c)

R rotor radius, ft

V forward velocity of rotor, ft/sec

w induced velocity at center of rotor, positive upward, ft/sec

w_0 induced velocity at center of rotor with no ground effect, positive upward, $\frac{-\frac{1}{2} C_T\Omega R}{\sqrt{\mu^2 + \lambda^2}}$, ft/sec

$w_{0,h}$ induced velocity at center of rotor when hovering with no ground effect, positive upward, $-\Omega R\sqrt{\frac{C_T}{2}}$, ft/sec

Δw interference velocity at center of rotor due to presence of ground, positive upward, ft/sec

Δw_h interference velocity at center of hovering rotor due to presence of ground, positive upward, ft/sec

x,y,z Cartesian coordinates centered in rotor, ft

Z height of rotor above ground, ft

α rotor tip-path-plane angle of attack (positive when tip-path-plane axis is behind the vertical), deg

γ wind-tunnel width-height ratio, $\frac{B}{H}$

δ_w wind-tunnel jet-boundary correction factor (eq. (1b))

λ rotor inflow ratio, $\dfrac{V \sin \alpha + w_0}{\Omega R}$

μ rotor tip-speed ratio, $\dfrac{V \cos \alpha}{\Omega R}$

ρ mass density of air, slugs/cu ft

σ ratio of rotor diameter to tunnel width, R/B

χ wake skew angle, $\tan^{-1} \dfrac{-\mu}{\lambda}$, deg

ψ rotor azimuth angle, measured from downwind position, radians

Ω rotor rotational speed, radians/sec

Note that, in contrast to usual practice in rotary wing studies, all induced and interference velocities in this paper are considered positive when directed upward.

THEORY

Equation (19) of reference 5 shows that, for a wind tunnel of height 2H and width 2B, the jet-boundary interference velocity caused by only the solid floor of the wind tunnel may be expressed as

$$\frac{\Delta w}{w_0} = \delta_w \frac{A_R}{A_T} \tag{1a}$$

where

$$\delta_w = \frac{2\gamma}{\pi}\left[K\left(\frac{x}{H} - \tan \chi, \frac{y}{H}, \frac{z}{H} + 1\right) + K\left(\frac{x}{H}, \frac{y}{H}, \frac{-z}{H} - 2\right) - K\left(\frac{x}{H} - \tan \chi, \frac{y}{H}, \frac{-z}{H} - 1\right)\right] \tag{1b}$$

and where, from equation (7b) of reference 5

$$K\left(\frac{x}{H},\frac{y}{H},\frac{z}{H}\right) = \frac{1}{\pi\sigma\gamma}\int_0^{2\pi} \frac{\left[\frac{x}{H}\cos\psi + \frac{y}{H}\sin\psi - \sigma\gamma - \sin\chi\cos\psi\sqrt{\sigma^2\gamma^2 + \left(\frac{x}{H}\right)^2 + \left(\frac{y}{H}\right)^2 + \left(\frac{z}{H}\right)^2 - 2\sigma\gamma\left(\frac{x}{H}\cos\psi + \frac{y}{H}\sin\psi\right)}\right]d\psi}{\left[\sqrt{\sigma^2\gamma^2 + \left(\frac{x}{H}\right)^2 + \left(\frac{y}{H}\right)^2 + \left(\frac{z}{H}\right)^2 - 2\sigma\gamma\left(\frac{x}{H}\cos\psi + \frac{y}{H}\sin\psi\right)} + \frac{z}{H}\cos\chi - \frac{x}{H}\sin\chi + \sigma\gamma\sin\chi\cos\psi\right]\sqrt{\sigma^2\gamma^2 + \left(\frac{x}{H}\right)^2 + \left(\frac{y}{H}\right)^2 + \left(\frac{z}{H}\right)^2 - 2\sigma\gamma\left(\frac{x}{H}\cos\psi + \frac{y}{H}\sin\psi\right)}} \tag{1c}$$

The rotor wake configuration for which equation (1) represents the interference velocity is shown in figure 1. It will be observed that this is precisely the wake pattern that would be assumed (as an extension to refs. 1 and 2) for simple ground effect. Notice that the rotor, for simplicity, is assumed to be at zero angle of attack, and the results are therefore valid only for small rotor tilts.

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Numerical values of the jet-boundary correction factor, δ_w, for this wake configuration are presented in reference 5. These results are, however, presented in terms of the dimensions of a wind tunnel which, for all practical purposes, does not exist in the present case. In order to eliminate the tunnel dimensions, note the identities

$$\frac{A_R}{A_T} = \frac{\pi R^2}{4BH} = \frac{\pi}{4}\,\sigma^2\gamma \tag{2a}$$

$$\frac{Z}{R} = \frac{H}{R} = \frac{1}{\sigma\gamma} \tag{2b}$$

Thus, for each value of δ_w in table III of reference 5, one ground-effect interference velocity may be obtained as

$$\frac{\Delta w}{w_0} = \frac{\pi}{4}\,\sigma^2\gamma\delta_w \tag{3}$$

(from eqs. (1a) and (2a)), and this interference velocity corresponds to the height above the ground given by equation (2b).

It will be observed that the smallest value of Z/R obtainable in this manner from the tables of reference 5 is $Z/R = 0.526$. A few additional calculations, using selected values of B and H and only the K terms shown in equation (1b), were made in order to obtain the interference velocities for heights above the ground of one-tenth to one-half the rotor radius. These calculations were made by slightly modifying the computer program used for reference 5 and, as run on the IBM 704 electronic data-processing machine, required only 3 to 4 seconds per condition.

RESULTS AND DISCUSSION

Calculated Results

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The calculated interference velocities (nondimensionalized with respect to the induced velocity at the corresponding condition with no ground effect) are presented in figure 2. For all conditions, ground effect is favorable; that is, the interference velocity is an upwash which will tend to reduce the induced power required by the rotor. Ground effect is a maximum in hovering ($\chi = 0^\circ$), and a minimum in high-speed forward flight ($\chi = 90^\circ$). In forward flight, the ground effect decreases more rapidly with height above the ground than it does in hovering. When the rotor is in flight at a distance more than one-half radius above the ground, the favorable ground effect has essentially reached its minimum value by the time the skew angle has risen to the order of 70°.

The interference velocities presented in figure 2 are valid only for the center of the rotor. Examination of the induced velocity distribution in hovering, as shown in references 1 and 2, indicates that, for $\chi = 0^\circ$, these velocities at the center are the maximum interference velocities encountered anywhere on the disk. These velocities, although useful for a qualitative discussion of the problem, are not directly applicable to computations of the power requirement of the rotor. In order to circumvent this difficulty, figure 3 presents the ratio of the nondimensional interference velocities in forward flight to the corresponding interference velocities in hovering. Thus, on the assumption that the average interference velocity over the disk remains proportional to the interference velocity at the center, a known ground effect in hovering may be used to determine the ground effect in forward flight by means of this figure. The presentation used in figure 3 has an additional minor advantage in that it magnifies the ordinate as Z/R increases, and thus makes it somewhat easier to read values from the curves.

Notice that even though the interference velocity approaches zero as the height above the ground approaches infinity, the interference ratio of figure 3 approaches a finite limit. This limit may be determined from reference 5, which gives the interference velocity for a very small rotor ($\sigma = 0$, thus $Z/R = \infty$) and a single lower boundary as

$$\frac{\Delta w}{w_0} = \delta_w \frac{A_R}{A_T} = -\frac{2\gamma}{\pi}\left(\frac{3}{2}\cos^4\chi + \frac{1}{4}\right)\frac{A_R}{A_T} \tag{4}$$

Thus,

$$\frac{\dfrac{\Delta w}{w_0}}{\dfrac{\Delta w_h}{w_{0,h}}} = \frac{-\dfrac{2\gamma}{\pi}\left(\dfrac{3}{2}\cos^4\chi + \dfrac{1}{4}\right)\dfrac{A_R}{A_T}}{-\dfrac{7}{2\pi}\gamma\dfrac{A_R}{A_T}} = \frac{1}{7} + \frac{6}{7}\cos^4\chi \tag{5}$$

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Comparison With Reference 4

Reference 4 obtains an interference velocity for the rotor in ground effect which may, in the present notation, be expressed when $\alpha = 0$ as

$$\frac{\Delta w}{w_0} = \frac{A_R \cos^2\chi}{16\pi Z^2} \tag{6}$$

Thus,

$$\frac{\dfrac{\Delta w}{w_0}}{\dfrac{\Delta w_h}{w_{0,h}}} = \frac{\dfrac{A_R \cos^2\chi}{16\pi Z^2}}{\dfrac{A_R}{16\pi Z^2}} = \cos^2\chi \tag{7}$$

a result which is surprisingly independent of the height above the ground.

The interference ratio, as obtained from equation (7), is indicated by the dashed lines in figure 3. This very simple result compares reasonably well with the present more elaborate analysis for skew angles of less than 60°; the values given by equation (7) correspond roughly with the values computed herein for heights of one to two radii. For higher skew angles, near 90°, the interference ratio given by equation (7) becomes zero. This result is not plausible since the rotor is essentially equivalent to a wing under these conditions and a ground effect occurs for the wing. The practical significance of this error may not be great, since at high skew angles the induced velocities are small.

Induced Velocity as Affected by Forward Speed

Thus far, the results have been presented in terms of the wake skew angle and the zero-ground-effect induced velocity at that skew angle. Both parameters are largely affected by forward velocity; thus, in effect, figures 2 and 3 have distorted scales which tend to mask the true variation with forward speed. It is preferable to recast the results in terms of V and $w_{0,h}$. This may be done as follows:

Note that

$$\chi = \tan^{-1} \frac{-V \cos \alpha}{V \sin \alpha + w_0}$$

so that, under the present circumstances, where $\alpha = 0$,

$$\frac{V}{-w_0} = \tan \chi$$

and

$$\frac{V}{-w_{0,h}} = \frac{V}{-w_0}\left(\frac{w_0}{w_{0,h}}\right) = \frac{w_0}{w_{0,h}} \tan \chi \qquad (8)$$

also

$$\frac{\Delta w}{w_{0,h}} = \frac{\Delta w}{w_0}\left(\frac{w_0}{w_{0,h}}\right) \qquad (9)$$

The ratio $\frac{w_0}{w_{0,h}}$ may be obtained from reference 6, which, in the present notation, gives for $\alpha = 0$

$$\frac{w_0}{w_{0,h}} = \sqrt[4]{\frac{1}{1 + \left(\frac{V}{-w_0}\right)^2}} = \sqrt[4]{\frac{1}{1 + \tan^2 \chi}} = \sqrt{\cos \chi} \qquad (10)$$

Figure 4, which was prepared by selecting appropriate points from figure 2 and transforming these values according to equations (8), (9), and (10), shows the variation of interference velocity with forward velocity. This figure indicates the rapidity with which ground effect decreases with forward speed. The bulk of this decrease is seen to occur by the time that the rotor has reached a forward speed equal to 1.5 times its hovering mean induced velocity.

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Figure 5 shows the total induced velocity at the rotor center, or

$$\frac{w}{w_{0,h}} = \frac{w_0}{w_{0,h}} + \frac{\Delta w}{w_{0,h}} \qquad (11)$$

It may now be seen that the decrease in interference velocity is more rapid than the decrease in induced velocity which occurs with increased speed. As a result, the total induced velocity at the center of the rotor, at low heights above the ground, actually increases with forward speed as the rotor first picks up speed. This phenomenon has also been noted in reference 4, which states that it has been observed in flight.

Effect of Angle of Attack

This analysis has considered only the case of zero angle of attack. Reference 5 shows that two changes are required in order to account for the effect of angle of attack. The first change is to substitute an effective skew angle $\chi - \alpha$ for χ. The second change is to alter the interference velocity by a factor which is equal to twice the angle of attack (in degrees). Thus, if the rotor is tilted forward, ground effect will decrease even more rapidly with forward speed than is shown in figure 5. Conversely, if the rotor is tilted rearward, ground effect will decrease less rapidly.

CONCLUSIONS

This analysis of ground effect on lifting rotors indicates that in forward flight:

1. Ground effect decreases with height above the ground more rapidly than it does in hovering.

2. Ground effect decreases rapidly with forward speed, the bulk of the reduction occurring at speeds below 1.5 times the hovering mean induced velocity.

3. The reduction of ground effect with forward speed is so rapid that, at low heights above the ground, the total induced velocity at the center of the rotor increases rather than decreases as the helicopter increases speed.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., December 1, 1959.

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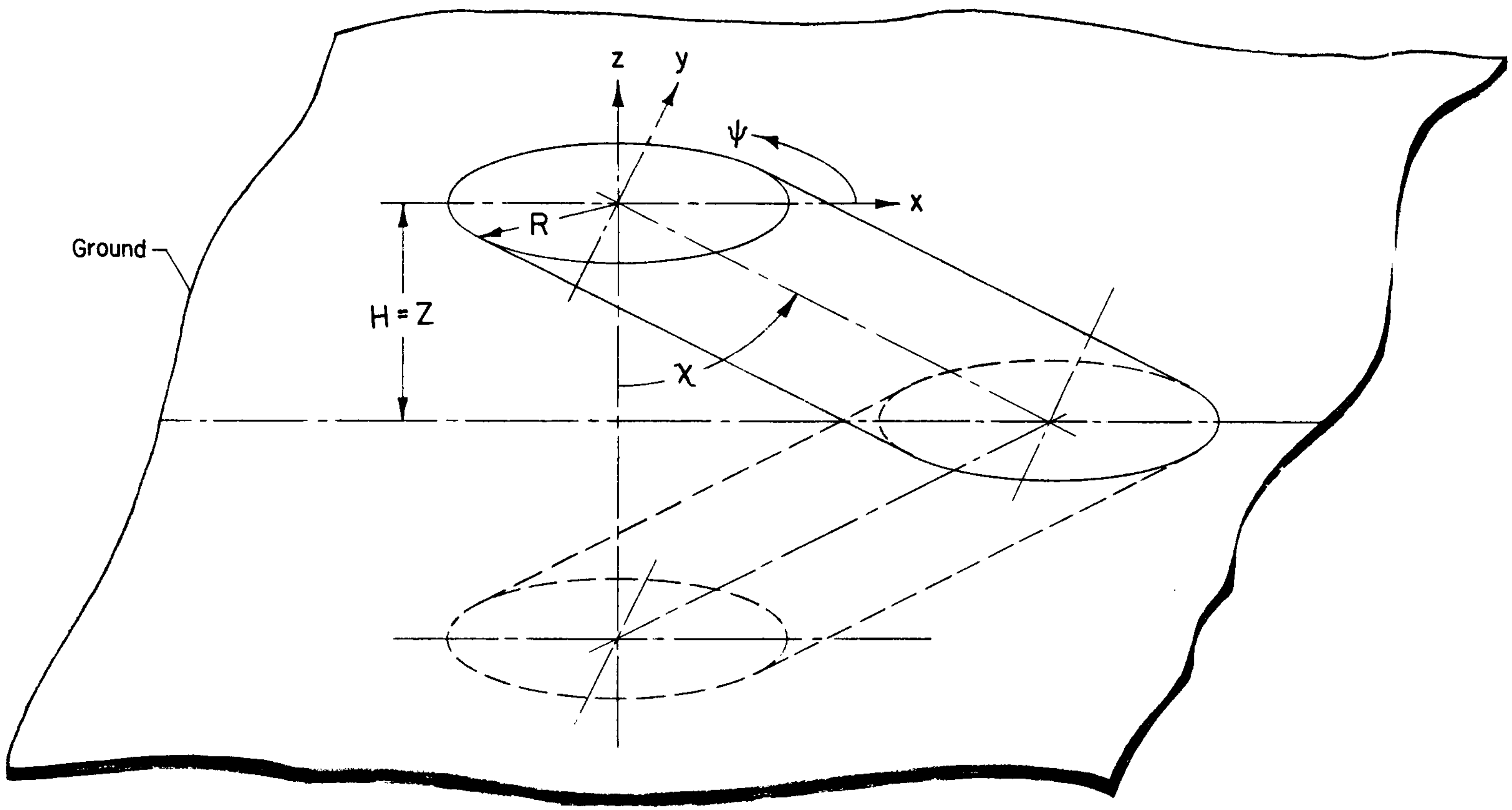

Figure 1.- Representation of wake of rotor in the presence of ground.

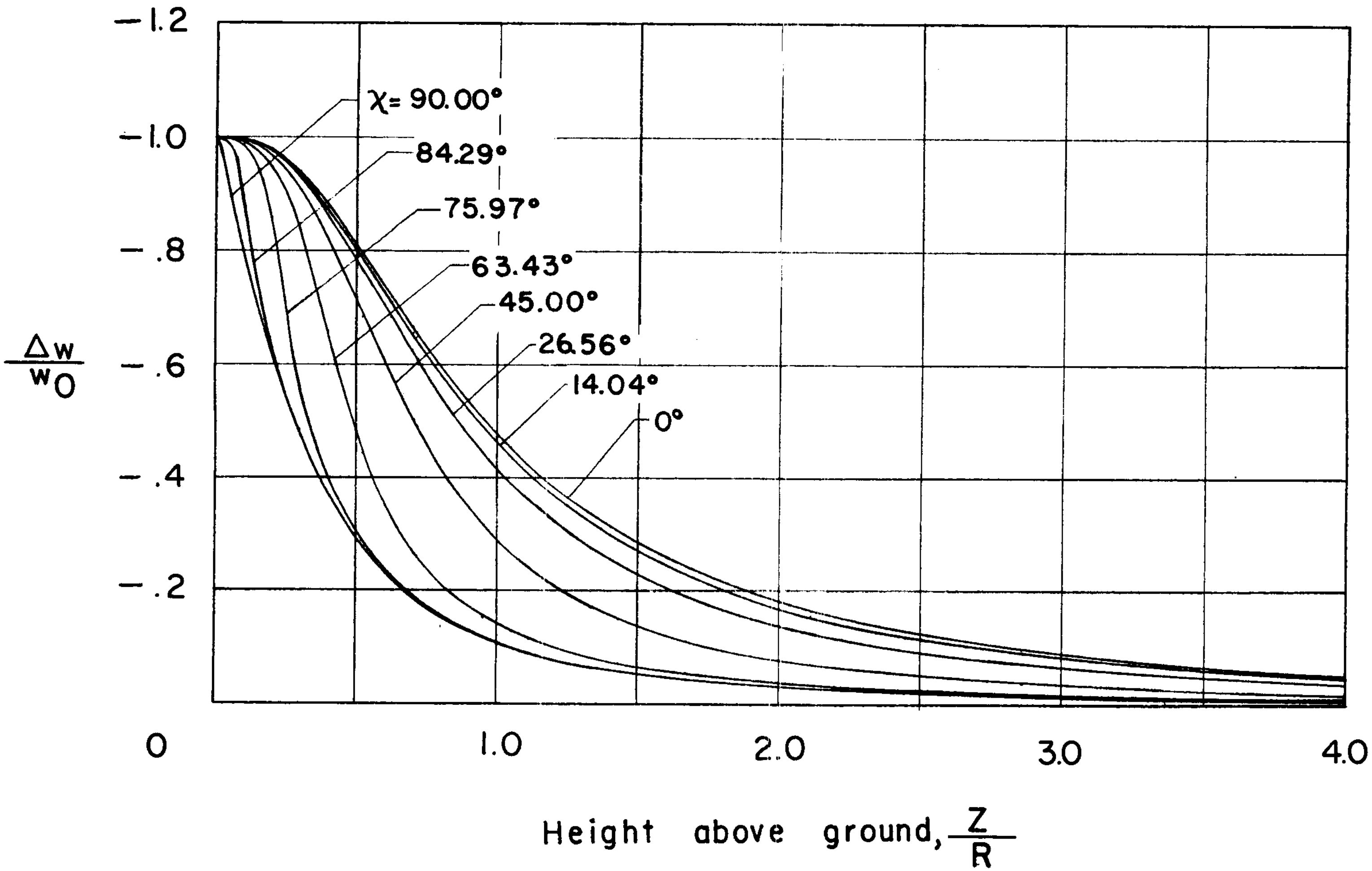

Figure 2.- Ground-induced interference velocity at center of rotor.

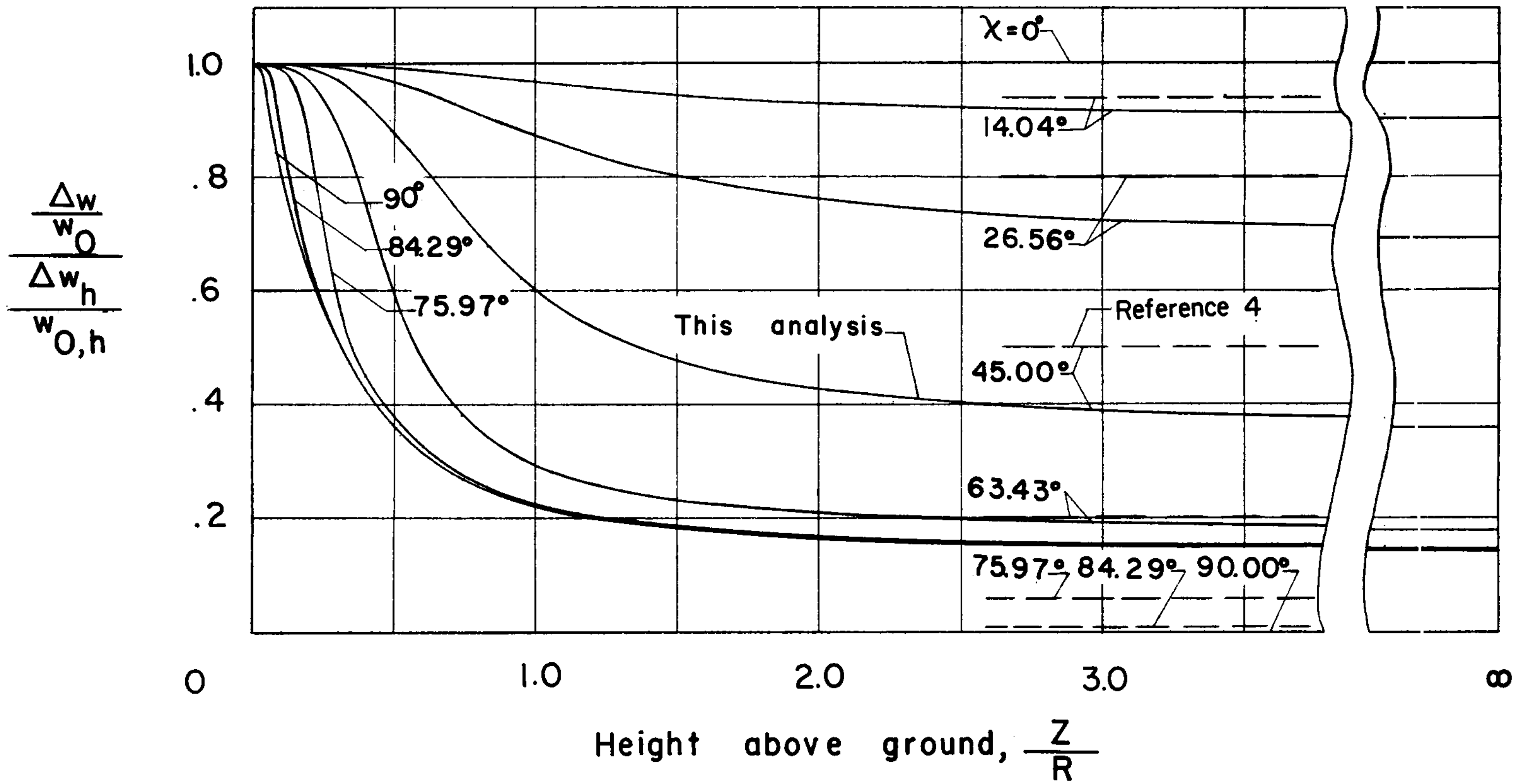

Figure 3.- Effect of ground on ratio of nondimensional ground-effect interference velocity in forward flight to the similar velocity in hovering, and a comparison with the results of reference 4.

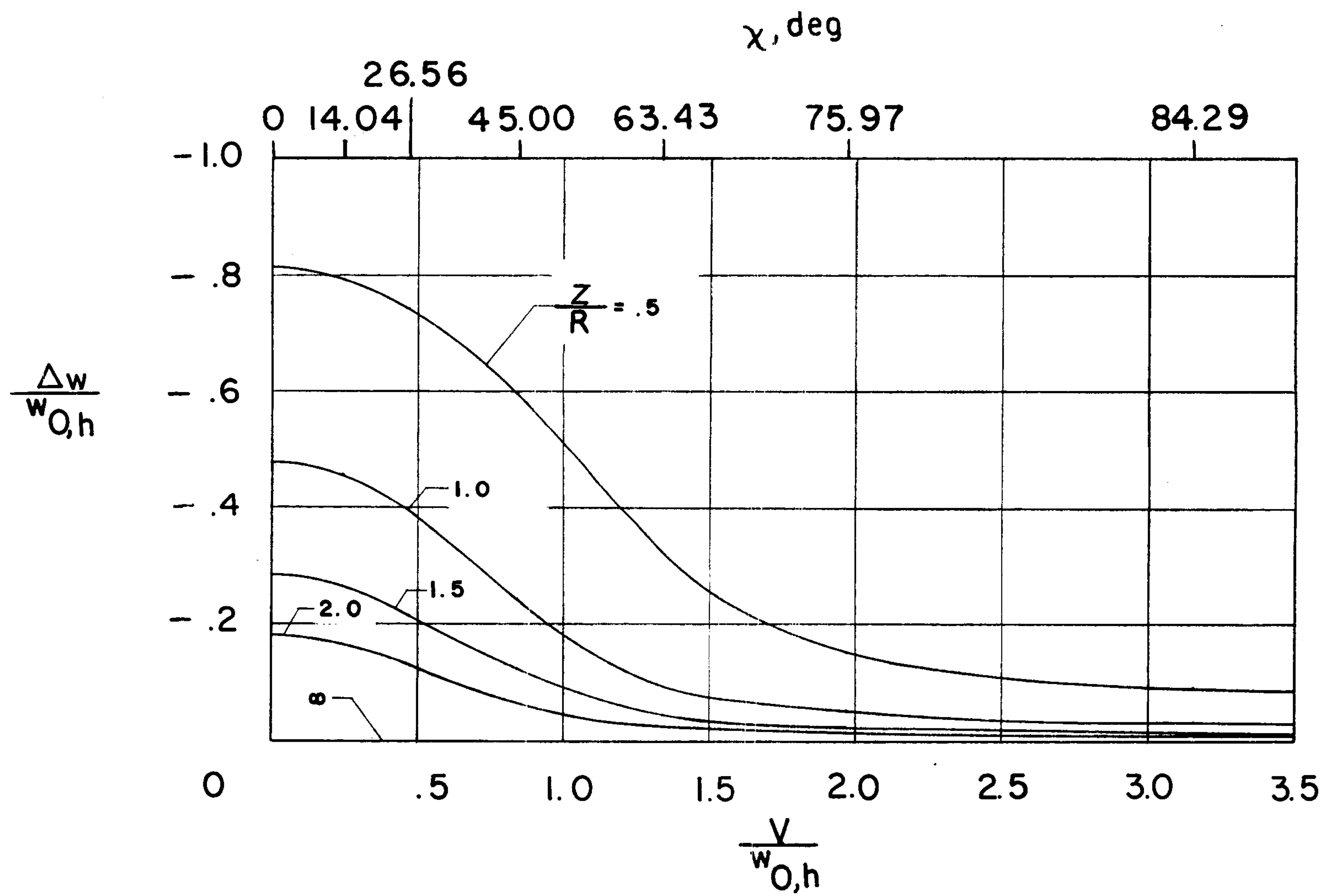

Figure 4.- Ground-induced interference velocity at center of rotor as a function of forward speed.

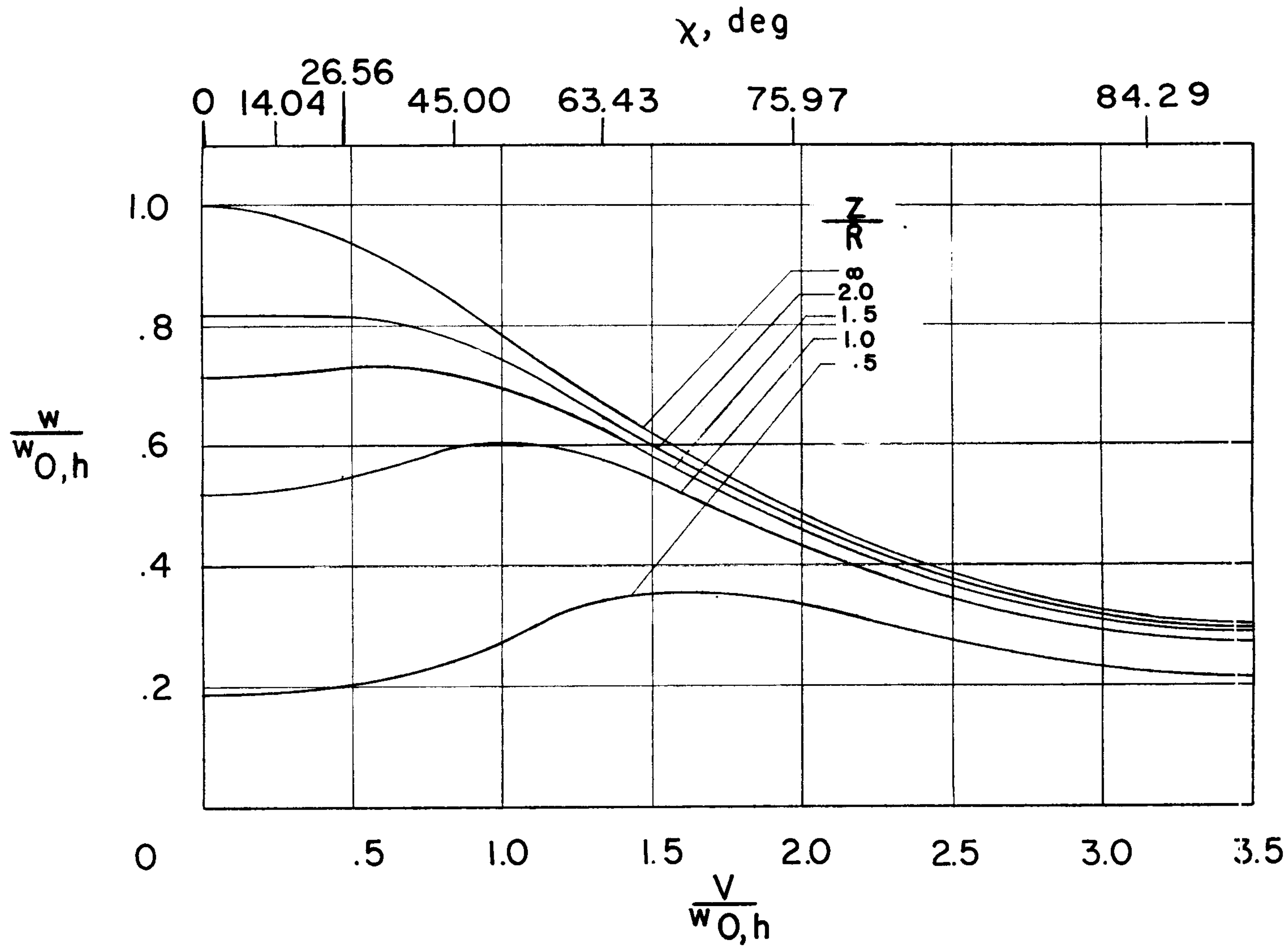

Figure 5.- Total induced velocity at center of rotor in forward flight near the ground.