[6]McCormack, D. C., and Bennett, J.C., Jr., "Vortical and Turbulent Structure of a Lobed Mixer Free Shear Layer," *AIAA Journal,* Vol. 32, No. 9, 1994, pp. 1852–1859.

Field Measurements of Helicopter Rotor Wash in Hover and Forward Flight

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Introduction

THE U.S. Department of Agriculture Forest Service uses helicopters to spray forests with pesticides, spread water or retardants on forest fires, and, along with the U.S. Army, maintains an interest in the propagation of fire along the ground and the movement of contaminants in the air. The dispersing aircraft generally fly low over their target area in an effort to deliver their payloads with as much precision as possible. In this flight configuration, helicopters induce downwash and sidewash velocities that may be significant when weighing the advantages of one helicopter vs another with regard to potential of sideways spread of the released spray material, the injurious possibility of the induced velocities actually enhancing the ability of a fire to spread, or the ability to disperse dusts, aerosols, or other contaminants from a specified location. In the case of forest fire-fighting, this hypothesis suggests that helicopters may create a significant induced sidewash surface velocity, which actually propels the fire sideways, moving it through the fuel and preventing control.

Up to now, the effect of a passing helicopter on the local meteorology, particularly near a forest fire, has been understood only from a qualitative standpoint. Because the quantitative data are considered important in understanding fire propagation and the dispersal of pesticides and other contaminants, a cooperative field study was recently conducted to collect such data, with the hope that these data may be used to validate models of helicopter wakes, suggest operational methods for fighting forest fires, and provide insight into the dispersal of dusts, aerosols, and other contaminants in the atmosphere.

Discussion

During July 26 to July 29 and Sept. 27 to Oct. 1, 1994, 181 passes were made by seven helicopters (Bell 205H, Bell 206B, Blackhawk, Boeing Vertol BV-107, Chinook CH-47, Sikorsky S-61, and Skycrane) over an instrumented tower grid at Yuba City, California. Propeller anemometers measured the induced downwash and sidewash velocities generated by the helicopters in hover or forward flight above the tower grid, in a fashion similar to the technique used to collect data to infer the decay behavior of aircraft vortices near the ground.[1] Resulting time histories from the anemometers were examined to recover the magnitude and behavior of the induced velocities. The complete data set, including descriptive data about the helicopters, is summarized in Table 1.

Collected data were reduced and presented previously in Teske and Kaufman[2] and Teske et al.[3] These data show an easily identifiable sidewash velocity obeying a simple exponential decay law. The four parameters developed from these data were 1) the maximum induced surface velocity, 2) its exponential decay time constant, 3) the apparent depth of the layer containing the sidewash motion, and 4) its frontal speed outward from the helicopter. Data average results suggest that a significant induced surface sidewash velocity may result from the passage of a helicopter (depending on the size, weight, and flight speed of the helicopter, and its height above the ground), that the peak-induced sidewash velocity moves slowly along the ground in a tall gust front, and that the induced sidewash velocity remains important for a long period of time. While these results are not surprising to anyone who has been in the neighborhood of a helicopter or observed its effects in a theatrical movie, they are quantified by the field study.

The most important result is the estimate of maximum induced surface velocity, as this result may be used to infer preferential flight conditions for a helicopter in a forest fire-fighting situation. To generalize this result from all field tests, we have applied a regression algorithm to the collected data that develops the least-squares best fit to an equation of the following form

$$V = aS^bH^c \tag{1}$$

where V is the maximum induced surface velocity, S is the helicopter ground speed, and H is the helicopter drop height. In this equation, H is normalized by the helicopter rotor radius R, and V and S are normalized by the induced downwash velocity w, taken from actuator disk theory

$$w = \frac{1}{R}\left[\frac{W}{2\pi\rho}\right]^{1/2} \tag{2}$$

where W is the helicopter weight and ρ is air density. For all helicopters examined in this study, the regression algorithm recovers

$$a = 1.635, \qquad b = -0.442, \qquad c = -0.792$$

with a correlation of $R^2 = 0.677$. Figure 1 displays the results and indicates the level of anticipated induced surface velocity, given a value for helicopter ground speed and drop height. For example, for the Blackhawk, if a maximum induced surface velocity of 4.32 m/s is allowed in a specific situation ($V = 0.4$), with a drop height of 32.0 m ($H = 4.0$), the helicopter should be traveling at a minimum ground speed of 21.6 m/s ($S = 2.0$).

Alternatively, Fig. 1 may be used to estimate induced surface velocity. For example, a Blackhawk traveling at a ground

Table 1 Field study summary

Helicopter	R, m	w, m/s	Flybys
Bell 205H	7.4	8.85	30
Bell 206B	5.5	6.12	19
Blackhawk	8.0	10.80	36
Boeing Vertol BV-107	7.6	14.79	29
Chinook CH-47	9.1	12.88	24
Sikorsky S-61	9.4	11.17	16
Skycrane	11.0	13.14	27
Total	——	——	181

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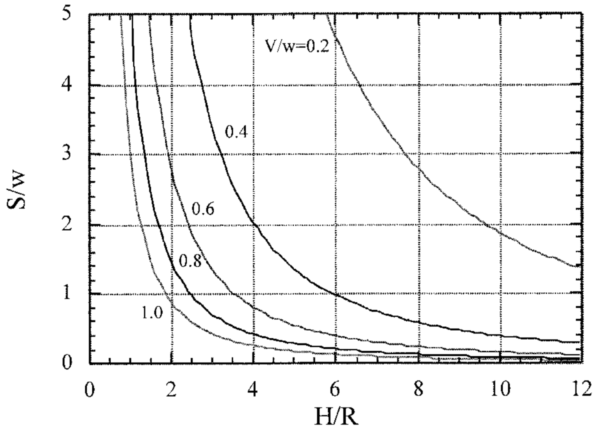

Fig. 1 Maximum induced surface velocity contours.

speed of 32.4 m/s (S = 3.0) and a drop height of 48.0 m (H = 6.0) will generate an estimated maximum induced surface velocity of approximately 2.6 m/s (V = 0.24). The utility of these results is then obvious and may be used to infer the potential for any helicopter to promote the sideways spread of fire, pesticides, dusts, aerosols, or other contaminants.

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References

[1]Teske, M. E., Bilanin, A. J., and Barry, J. W., "Decay of Aircraft Vortices near the Ground," *AIAA Journal*, Vol. 31, No. 8, 1993, pp. 1531–1533.

[2]Teske, M. E., and Kaufman, A. E., "Field Measurements of Helicopter Rotor Wash in Hover and Forward Flight," U.S. Dept. of Agriculture, Forest Service, FPM 95-7, Davis, CA, 1994.

[3]Teske, M. E., Kaufman, A. E., George, C. W., Grim, B. S., and Barry, J. W., "Field Measurements of Helicopter Rotor Wash in Hover and Forward Flight," *Proceedings of the Northeast Region 2nd International Aeromechanics Specialists' Conference*, American Helicopter Society, Bridgeport, CT, 1995, pp. 1-79–1-86.

Neglect of Wake Roll-Up in Theodorsen's Theory of Propellers

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Introduction

THIS note addresses a paper by Schouten,[1] concerning the optimum propeller efficiency obtainable, neglecting profile drag, under specified operating conditions.[2–4] Schouten[1] directs criticism at the well-known theory of Theodorsen,[4–6] which models the propeller wake as a rigid backward moving (multiple) helicoid vortex sheet. He argues that the theory entails substantial error by failing to allow for the vortex sheet roll-up that occurs in reality. The roll-up, Schouten says, ensures that the static pressure in the wake tends toward ambient[7]: that it eliminates an unrealistic pressure rise permitted by the helicoidal scenario. This in turn is claimed to lead to an underestimation of the required power. As a corollary, the predictions of this ideal efficiency are judged to be substantially too high.

We find the arguments[1,7] concerning wake static pressure to be only partially correct and the conclusions concerning propeller power and efficiency untenable. Although the arguments are persuasive, the numerical comparisons, implicitly equating apples and oranges, are not valid. We conclude that neglect of wake roll-up only slightly mispredicts the efficiency. The basis for these remarks is developed further in the following text.

The underlying scenario goes back to Betz,[2] for lightly loaded propellers. Betz showed that this ideal efficiency is associated with an optimum loading that yields a special trailing vortex pattern: one whose induced velocity is such that it behaves like a (multiple) rigid helicoid sheet or screw surface moving axially backward. Goldstein[3] developed the analytic theory, leading to practical, accurate, performance prediction. Theodorsen[4] generalized this to apply, allowing for wake contraction, to heavily loaded propellers. He presented rigorous proof that this rigid helicoid wake corresponds to maximum efficiency for his flow model.

The nonrigid behavior of the wake is a matter that Theodorsen[4] treats rather dismissively: ". . . the theory [he says] . . . may to some extent be 'overidealized'. The vortex surface is in fact unstable and will therefore not maintain its ideal shape for any length of time." Both Theodorsen[4] and Schouten[1] are referring to the rolling up of the helicoid vortex sheet. This is a phenomenon that has been ignored in the theory, and Schouten deserves credit for raising these matters with a penetrating analysis.

Issue must be taken with Schouten's arguments and with the numerical results flowing therefrom: these results are based on inappropriate values of κ and ε inserted in a somewhat flawed equation. Thus it is invalid to use these numbers (apples vs oranges) in comparisons with Theodorsen's theory[4] that neglect the vortex rolling up. In particular, Schouten's[1] conclusion that the theory substantially overpredicts the ideal efficiency is not supported.

Is the Helicoid Sheet Force-Free?

We do agree, however, with Schouten's assertion[1] that wake edge forces are required to suppress roll-up. It is only with the implications that we disagree. Quoting Betz[8] for the analogous planar case,

> this motion would only be possible for any length of time if the area of discontinuity [here the helicoid] actually were rigid. By flowing around the edges, laterally directed suction forces P occur, which only could be taken up by a rigid plate [helicoid]. These forces are absent when the area of discontinuity is other than rigid, as a result of which the suction P effects other motions: starting at the edges, it unrolls and gradually forms two distinct vortices.

Theodorsen's postulation of no roll-up is thus an imposition of rigidity: as a consequence, it implies edge forces as claimed by Schouten.[1] The edge forces on opposite sides of a cylindrical helicoid are directed radially and are opposed: they affect neither the thrust nor the power. The equations for these, given in the following text, are therefore unaffected.

But this casual view overlooked the contraction region in which the edge forces are tilted: backward and circumferen-

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