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A Method for Three-Dimensional Modeling of Wind-Shear Environments for Flight Simulator Applications

Richard S. Bray, Ames Research Center, Moffett Field, California

NASA
National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

SYMBOLS

H	aircraft altitude above runway, ft
X	aircraft position along course (runway heading) relative to ILS glide slope intercept point, positive toward departure end of runway, ft
Y	lateral position relative to runway centerline extended, positive to left of approach course, ft

Inputs to wind-field model:

WX	ambient wind component toward positive X, ft/sec
WY	ambient wind toward positive Y, ft/sec
XC	along course position of vertical axis, ft
YC	across course position of vertical axis, ft
R	characteristic radius of downdraft, ft
HT	the upper altitude limit of horizontal flow associated with the down burst, ft
VZO	reference vertical flow velocity, positive downward, ft/sec
GX,GY	distortion factors which produce asymmetric flow by varying the effective value of R with azimuth; zero values are associated with axial symmetry
DELX, DELY	wind field position adjustment terms, nominally zero.
GVZ	wind field intensity gain factor, nominally 1.0

Outputs:

VX	wind velocity toward positive X, ft/sec
VY	wind velocity toward positive Y, ft/sec
VZ	vertical wind velocity, positive down, ft/sec
VZX	gradient with distance, along course, of vertical wind velocity, 1/sec
VZY	gradient with distance, across course, of vertical wind velocity, 1/sec
SLU	scale length, longitudinal component of random turbulence, ft
SLV	scale length, lateral component of random turbulence, ft
SLW	scale length, vertical component of random turbulence, ft
SGU	rms intensity, longitudinal component of random turbulence, ft/sec

SGV rms intensity, lateral component of random turbulence, ft/sec

SGW rms intensity, vertical component of random turbulence, ft/sec

SUMMARY

A computational method for modeling severe wind shears of the type that have been documented during severe convective atmospheric conditions is offered for use in research and training flight simulation. The procedure was developed with the objectives of operational flexibility and minimum computer load. From one to five simple "down-burst" wind models can be configured and located to produce the wind field desired for specific simulated flight scenarios. A definition of related turbulence parameters is offered as an additional product of the computations. The use of the method to model several documented examples of severe wind shear is demonstrated.

INTRODUCTION

The usual objective of wind-field modeling in simulation is the creation of environments that challenge the performance of normal operational tasks, such as landing or takeoff, in simulations conducted for training purposes or in the development and evaluation of aircraft systems. A number of wind-shear-induced accidents experienced in the past decade, together with the meteorological measurements of reference 1, have given firm evidence of the hazardous variations in horizontal and vertical winds that can occur in strong convective situations. Recorded data from the accidents, usually of doubtful accuracy, have been used to justify models dependent on a single variable, range, or two variables, range and altitude. The data reported in reference 1, on the other hand, supports the modeling of three components of the wind in a significant volume of three-dimensional space. An alternative to the storage of such data in the computer memory is an analytical model. The model computes, in real time, wind values that emulate the variations which would result from the data storage models, especially for the spatial volume significant to landing and takeoff. The subject modeling procedure was developed to meet that objective. Concurrent objectives were flexibility in use and economy in computation time.

For the aircraft position, the completely defined model computes three wind components (vertical, along course, and across course) for a wind field which includes from one to five local flow models. Each model describes the flow resulting from the impingement of a vertically moving column of air (down burst) on the ground plane. Definitions of associated turbulence parameters are offered for use with a conventional Dryden random turbulence model. The wind-field model format is not derived from considerations of atmospheric mechanics other than that of continuity. Incompressible flow is assumed, and wind velocities are invariant with time. The forms of downdraft geometry and vertical velocity distribution are arbitrary. They simply provide the means for creating low-altitude wind-field models that have spatial variations in wind velocity similar to those measured in the atmosphere during severe convective disturbances.

THE WIND-FIELD MODEL

The computational procedure for producing a complete wind-field model will be described in terms of the operational sequence seen in a digital program.

The Input File

Each total wind-field model is defined by an input data file that includes a statement of ambient, spatially invariant wind (WX, WY), together with the parameters defining each of up to five individual down bursts. An example input file is given as follows:

WX	-11.8
WY	11.8
XC	/2000, 3000, 4250, 11500, 1000/
YC	/4200, 4200, 4500, 4500, 4000/
R	/1400, 800, 1750, 1150, 1000/
HT	/2000, 2000, 2000, 1700, 2000/
VZO	/16.9, 23.7, 32.4, -39, 0/
GX	/-0.6, 0.7, 0.15, -0.8, 0/
GY	/ 0, 0, 0, 0, 0,/

(It is noted that the adjustment terms DELX, DELY, and GVZ are not included in the file, but are left independently available to the user.) In this input file, only four down burst models are actually defined. As seen later in the flow computations, all velocities in a given down burst are proportional to the input value of VZO. In this case, VZO(5) = 0. It is also noted that VZO(4) has a negative value, indicating an updraft which suggests a converging horizontal flow near the ground. This particular input file was configured to recreate the along-course and vertical winds measured in a meteorological research program (ref. 1). This wind-field model will be discussed later, together with other examples.

Initialization

The three components of the wind, and the along-course and across-course gradients of the vertical wind velocity are initialized as follows:

VZ = 0	VZX = 0
VX = WX	VZY = 0
VY = WY	

The wind contributions for each of the down bursts are then calculated and summed together with their initial values, in a computational loop or sequence. The flow associated with each down burst is calculated as vertical and radial velocities (VZZ, VR), from which the horizontal velocity components (VXX, VYY) are derived.

The Vertical Flow Column

Computing the radial distance of the aircraft, RC, from the vertical flow axis yields

$$XR = X - XC - DELX$$

$$YR = Y - YC - DELY$$

$$RC = (XR^2 + YR^2)^{1/2}$$

(To avoid any problems of division by zero, RC is assigned a minimum value of 1.0.)

The effective radius of the vertical flow, RA, is equal to the input value, R, if the distortion parameters GX and GY are zero. The resultant of GX and GY effectively translates the vertical wind "column" with respect to its defined axis. As will be shown, this results in a systematic variation of effective radius, RA, (and peak divergent wind velocities) with azimuth about the down-burst axis. The resultant distortion factor is

$$GR = (GX^2 + GY^2)^{1/2}$$

(Again, assign a minimum value, in this case, 0.001.)

RA, a function of aircraft position, down-burst location, and the distortion factors is determined by

$$COSA = \frac{XR}{RC} \cdot \frac{GX}{GR} + \frac{YR}{RC} \cdot \frac{GY}{GR}$$

$$RT = R \cdot COSA \cdot GR$$

$$RA = RT + [RT^2 + R^2(1 - GR^2)]^{1/2}$$

A minimum value of 1.0 is assigned to RA.

An arbitrary variation of vertical velocity with altitude is chosen:

If $H \geq HT$: $\quad VZH = GVZ \cdot VZO$

Otherwise: $\quad VZH = GVZ \cdot VZO\left[1 - \left(\frac{HT - H}{HT}\right)^2\right]$

The radial distribution of vertical flow velocity is chosen, using a computational radius ratio:

$$RR = \frac{RC}{0.7\ RA}$$

If RR < 1.0: $VZZ = VZH$

If RR > 2.0: $VZZ = 0$

If $2.0 \geq RR \geq 1.0$: $VZZ = VZH \dfrac{1 - \cos(RR \cdot \pi)}{2}$

Horizontal Flow

The previous definition of vertical flow, considering continuity, results in a linear variation of peak radial velocity with altitude, at distance RC = RA, from zero at HT to a maximum value at ground level, VRM, that is approximated by

$$VRM = \frac{GVZ \cdot VZO \cdot RA}{HT}$$

or a total wind change, across the diameter of the down draft column, of

$$\frac{2 \cdot GVZ \cdot VZO \cdot R}{HT}$$

VRM is not to be calculated, but rather to be used as a simple relationship when initially configuring the model. The radial velocity distribution is calculated first by defining the velocity at RR = 1.0 as a function of altitude

If $H \geq HT$: $VRR = 0$

Otherwise: $VRR = GVZ \cdot VZO \cdot \dfrac{0.7\ RA}{HT^2} \cdot (HT - H)$

A modest boundary-layer attenuation of velocity near the ground is assumed

If H < 50, then VRR is replaced by $VRR(0.75 + 0.005\ H)$

Local radial velocity, VR, as a function of distance from the vertical axis is calculated

If RR < 1.0: $VR = RR \cdot VRR$

If $1.0 \leq RR \leq 2.0$: $VR = VRR[RR - 1.3(RR - 1)^3 + 0.45(RR - 1)^6]$

If RR > 2.0: $VR = \dfrac{2.3 \cdot VRR}{RR}$

(In the second expression above, the exponential series approximates the more awkward series of cosine terms that results from integration of the continuity equation.)

The X and Y components of the radial velocity are

$$VXX = \frac{XR \cdot VR}{RC}$$

$$VYY = \frac{YR \cdot VR}{RC}$$

Vertical Velocity Gradients

The longitudinal and spanwise gradients of vertical velocity can have significant effects on the response of an aircraft. It is convenient in this model to define the along-course and across-course gradients. For the individual down burst, the gradients exist only for values of RR greater than 1.0 and less than 2.0. In this region, the radial gradient is defined as

$$VZZR = \frac{VZH \cdot \pi}{1.4\ RA} \cdot SIN(RR \cdot \pi)$$

The gradient components are

$$VZZX = \frac{XR}{RC} \cdot VZZR$$

$$VZZY = \frac{YR}{RC} \cdot VZZR$$

Summation of the Velocity Components

At the conclusion of the computation of the flows for each down burst, the winds and gradients are summed in the program statements

$$VX = VX + VXX$$

$$VY = VY + VYY$$

$$VZ = VZ + VZZ$$

$$VZX = VZX + VZZX$$

$$VZY = VZY + VZZY$$

Turbulence Parameters

The following definition of turbulence, suggested for association with the wind-field model, is based on the specifications cited in reference 2, and the observations cited in reference 3. At this time, the definition must be considered as a crude, educated guess. It is recommended that the user include common gain factors in his mechanization, to facilitate obtaining the desired level of disturbance.

Intensity levels, defined as functions of wind velocity and altitude, are

$$VT = (VX^2 + VY^2 + VZ^2)^{1/2}$$

If $H \geq 1000$: $SGT = SGU = SGV = SGW = 0.07 \cdot VT + 0.2 \cdot |VZ|$

If $H < 1000$: $SGU = SGV = \dfrac{SGT}{(0.25 + 0.00075 \cdot H)^{1/2}}$

If $H \leq 100$: $SGW = \dfrac{SGT \cdot H}{100}$

Variations of scale lengths with altitude, and vertical wind velocity, are

$$\text{If} \quad H \geq 1000: \quad SLT = SLU = SLV = SLW = 1000 - 0.3 \cdot VZ^2$$

$$\text{If} \quad H < 1000: \quad SLU = SLV = \frac{H}{0.15 + 0.00085 \cdot H} - 0.3 \cdot VZ^2$$

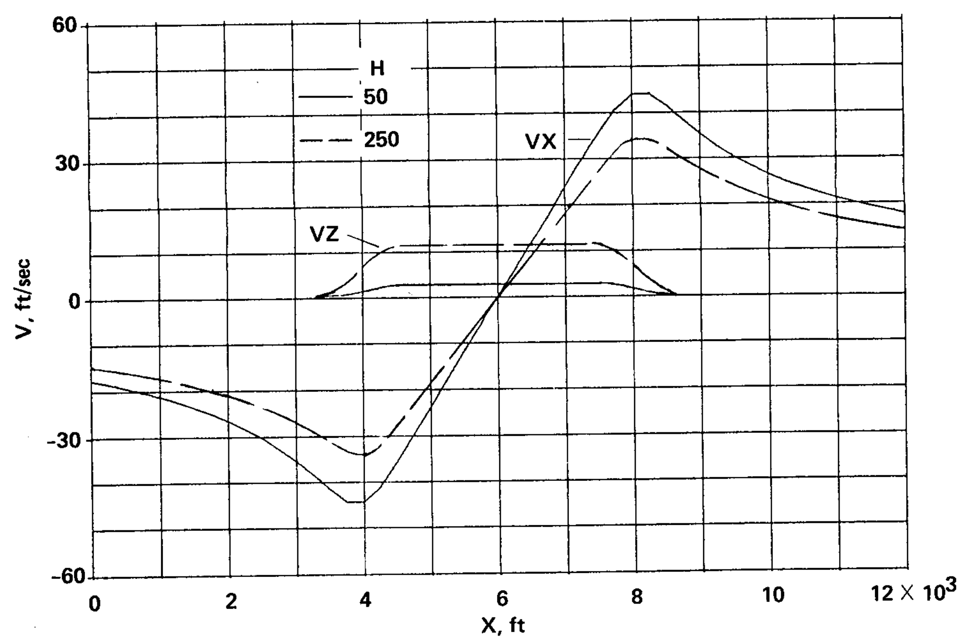
$$SLW = \frac{SLT \cdot H}{1000}$$

The minimum values of SLU and SLV are set at 100, and for SLW is set at 30.

MODELING WIND FIELDS

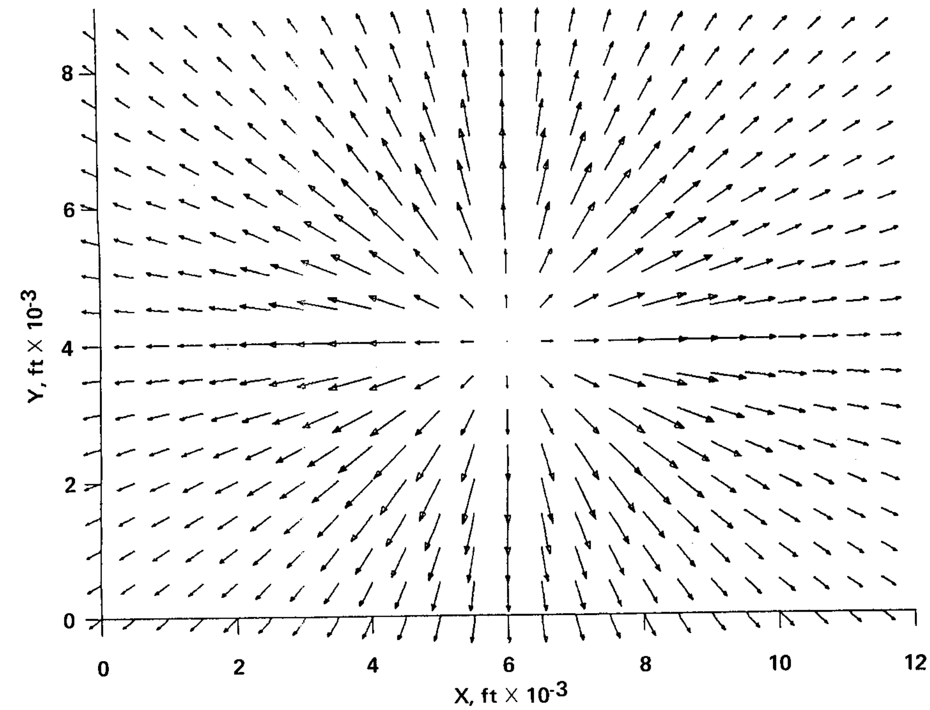
The Single Down-Burst Model

Illustrated in figure 1 are the winds produced by a single, axially symmetric, down-burst model, described by R = 2000 ft, HT = 1000 ft, and VZO = 25 ft/sec. The variation of the along-course wind and the vertical wind, along paths through the down burst center at an altitude of 50 and 250 ft, are shown in figure 1(a). Horizontal flow vectors, at 50 ft, are illustrated in figure 1(b). A vertical section, through the center of the down burst, is seen in figure 1(c). The contributions of distortion factors are shown in figure 2 for GX = GY = 0.4. Winds along a path at an altitude of 250 ft, through the center of the displaced downburst column are shown in figure 2(a). A crosswind component is seen in this case because the horizontal

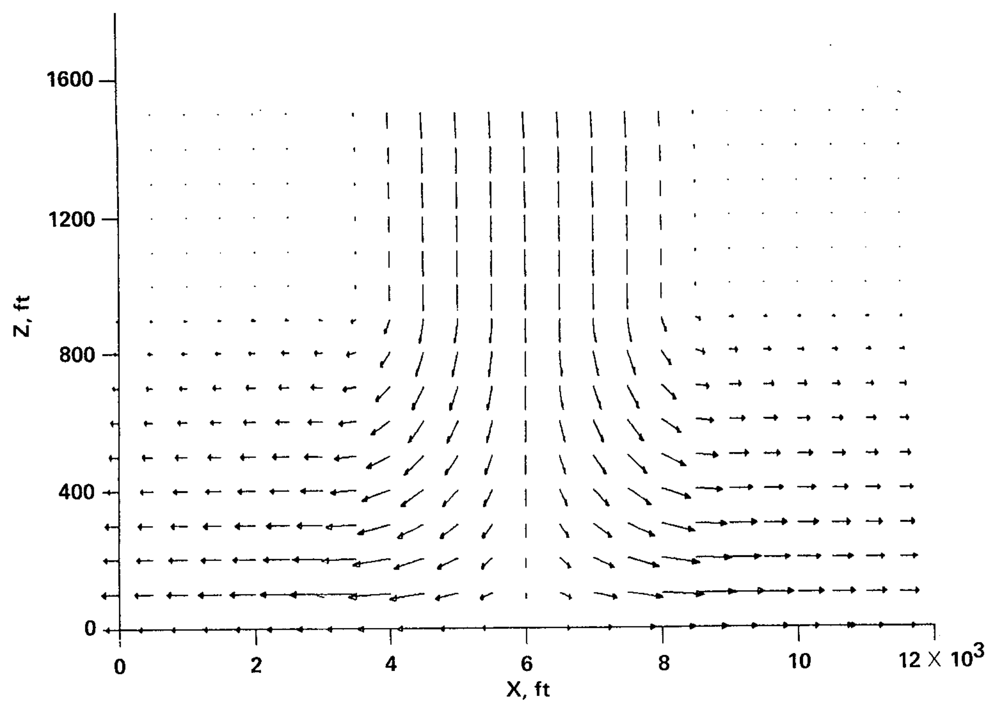


(a) Winds along paths through center of downburst.

Figure 1.- Winds produced by a single, down-burst model; R = 2000 ft, HT = 1000 ft, VZO = 25 fps.

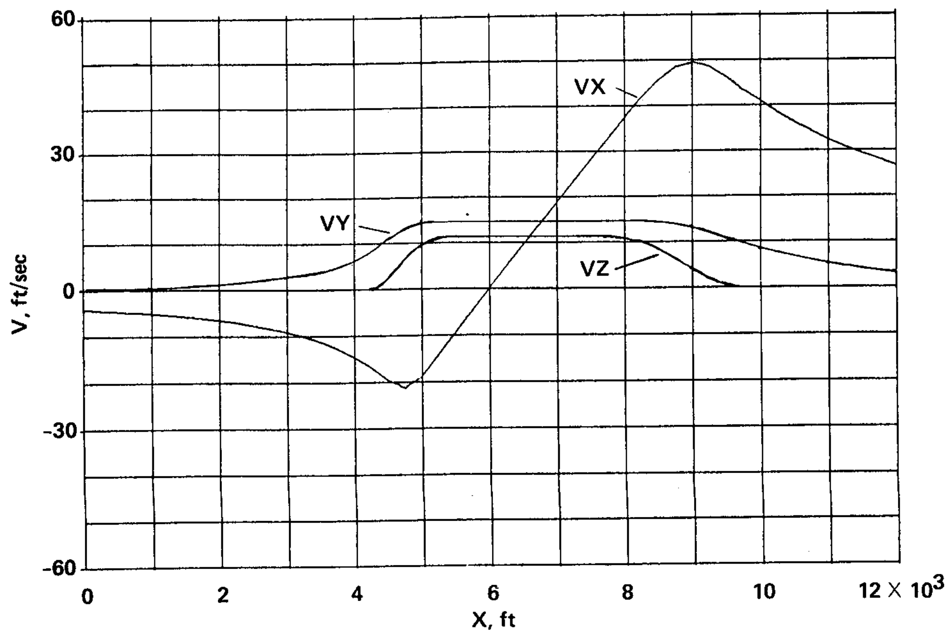


(b) Horizontal flow field at H = 50 ft.

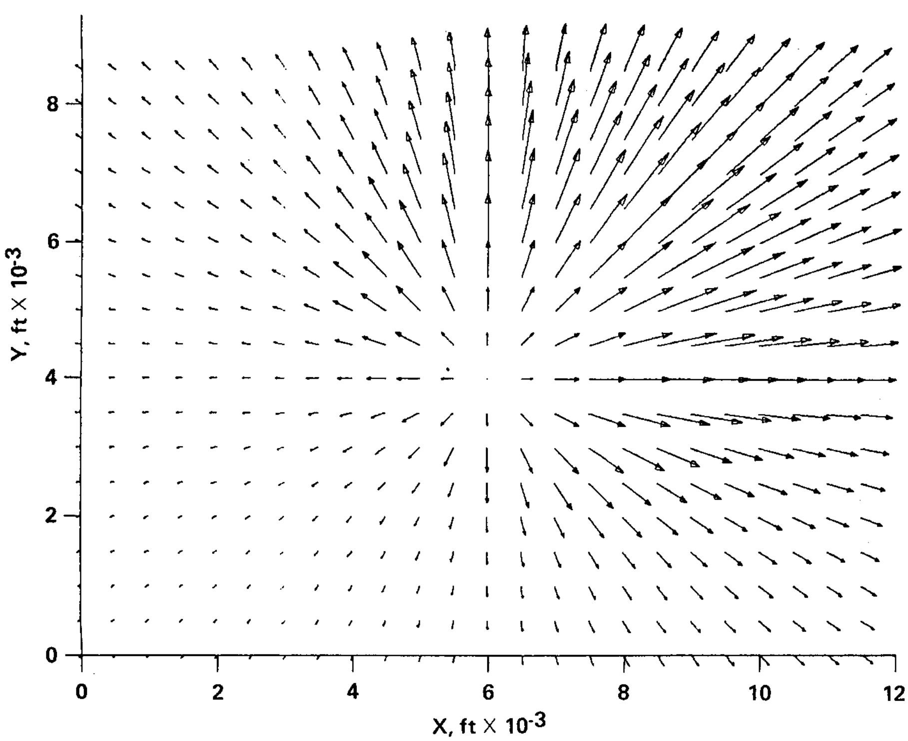


(c) Vertical cross section through center of down burst.

Figure 1.- Concluded.



(a) Winds at 250 ft, GX = GY = 0.4.



(b) Horizontal flow field, H = 50 ft.

Figure 2.- Effects of distortion factors, GX, GY.

dispersion center is to one side of the track. It can be seen that the along-track wind shear is the same magnitude as before; however, the peak head-wind/tail-wind relationship is altered. Horizontal flow vectors, at 50 ft, are shown in figure 2(b).

Appropriately sized and located, with respect to the approach or takeoff path, the single-down-burst model can produce reasonable recreations of the problems seen in some of the well-publicized accidents. It saw extensive use in simulator studies of cockpit displays at NASA Ames Research Center. There is, however, the desire to create more complex, less symmetrical models that can produce sequences of winds closely matching those measured in the atmosphere in specific circumstances. By use of multiple down-burst models, good matches of along-track and vertical winds can be made for complex cases.

Modeling Specific Wind-Shear Events- Doppler radar-measured winds, describing a strong, convective disturbance near Denver, Colorado, on August 5, 1982, are documented in reference 1. Figure 3 (taken from ref. 1) shows the horizontal wind vectors near ground level for a 44-km^2 area, together with identified paths through the area that encounter wind variations of several levels of severity. Path AB, which appears to traverse a down burst center, and then a vicinity of a flow convergence, is identified as one of the more severe wind-shear environments. Figure 4 shows the variation of the along-course wind measured for a 12,000-ft segment of AB, together with a profile generated by a wind-field model utilizing four downbursts. Both the measured and modeled values are appropriate for an altitude of 50 ft. The model successfully recreates the major wind variations that are significant to aircraft performance. A

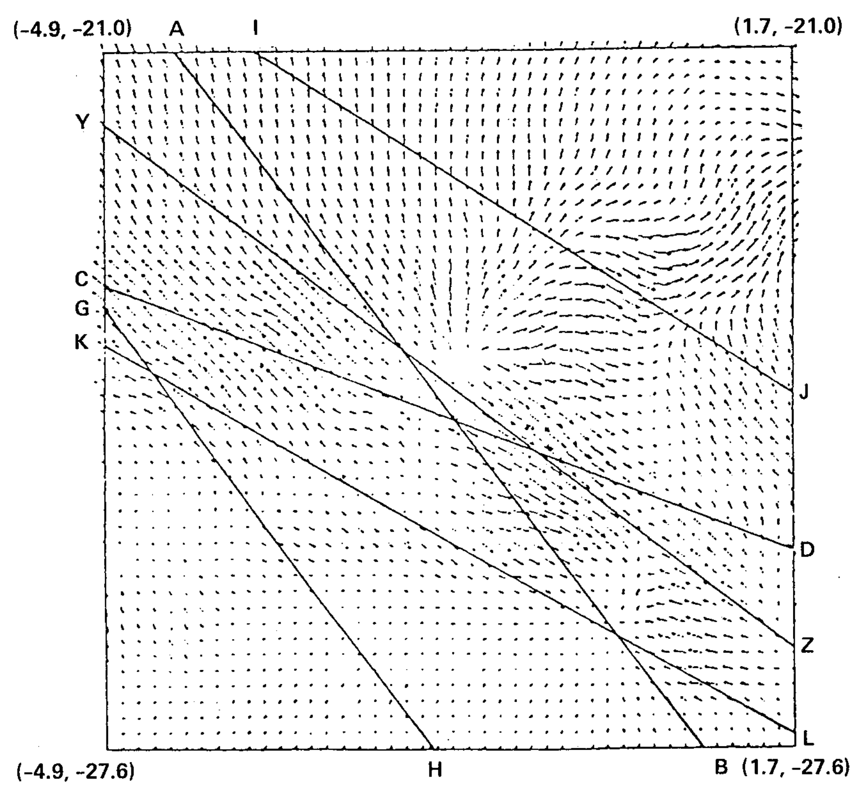


Figure 3.- JAWS data set coordinates in kilometers relative to CP-2 (see JAWS Project Operations Summary 1982, ref. 1).

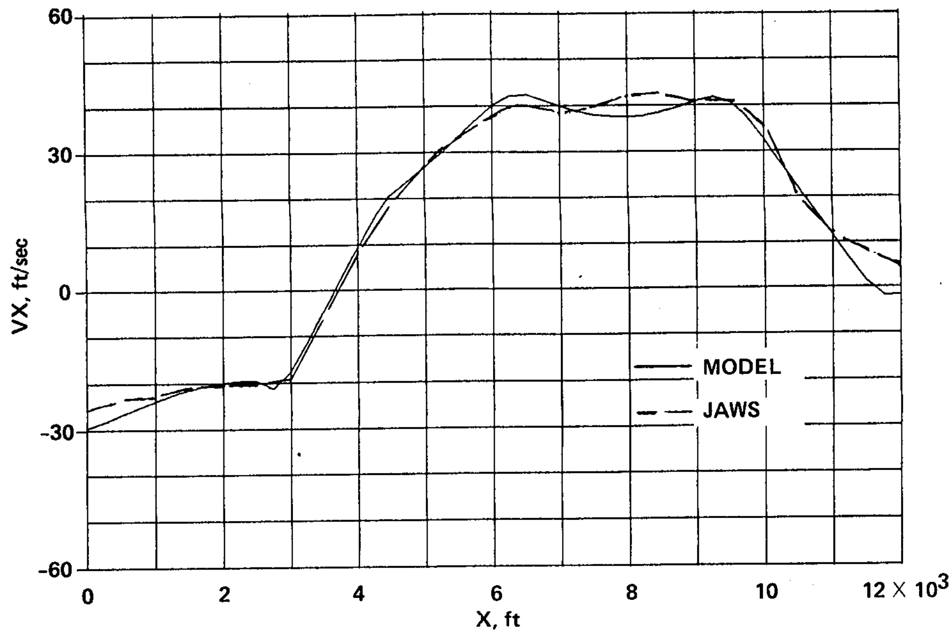


Figure 4.- Model match of a segment of JAWS Aug 5Ab, along-course wind at H = 50 ft.

horizontal wind-vector field, defined by the model, is shown in figure 5. Indicated are the four down burst model locations; one of the models, defining the flow convergence, is actually an updraft. The example input file, presented earlier in this report, defines this complete wind-field model. A comparison of derived and modeled vertical wind velocities, at 500 ft, is shown in figure 6.

Defining the individual down-burst characteristics, to produce a match with measured data, is an iterative, "by hand" process. Using the basic relationships defining the shear gradient and its extent (the parameter VRM discussed earlier), initial crude matches of the major gradients are attempted. The match can then be improved by adjusting the primary down-burst models, or by the addition of more models. The match in the example case involved five iterations. (Familiarity with the model, and the modeling process, expedites the achievement of close matches.)

The second example of wind-profile matching is shown in figure 7. The event data were derived from flight recordings obtained in an L-1011 airplane during an approach and go-around in severe wind shear at Kennedy Airport in 1975. This aircraft made its approach several minutes prior to a major wind-shear accident at the same location. In this case, the match is for winds along a descending flight path, and then the ascending path of the go-around. The input file describing these down-burst models is indicated in the figure. It was necessary, in creating the sequence in which a downdraft preceded the onset of severe shear, to use rather low values of HT for the primary down bursts. Another match of an accident-derived wind-shear profile, which included a "stagnation zone," or interruption in the shear gradient, was effected by locating a small updraft model within a much larger down-burst model.

Little mention has been made of the across-course wind variations associated with these models. In the first case, in which crosswinds are defined, no specific effort

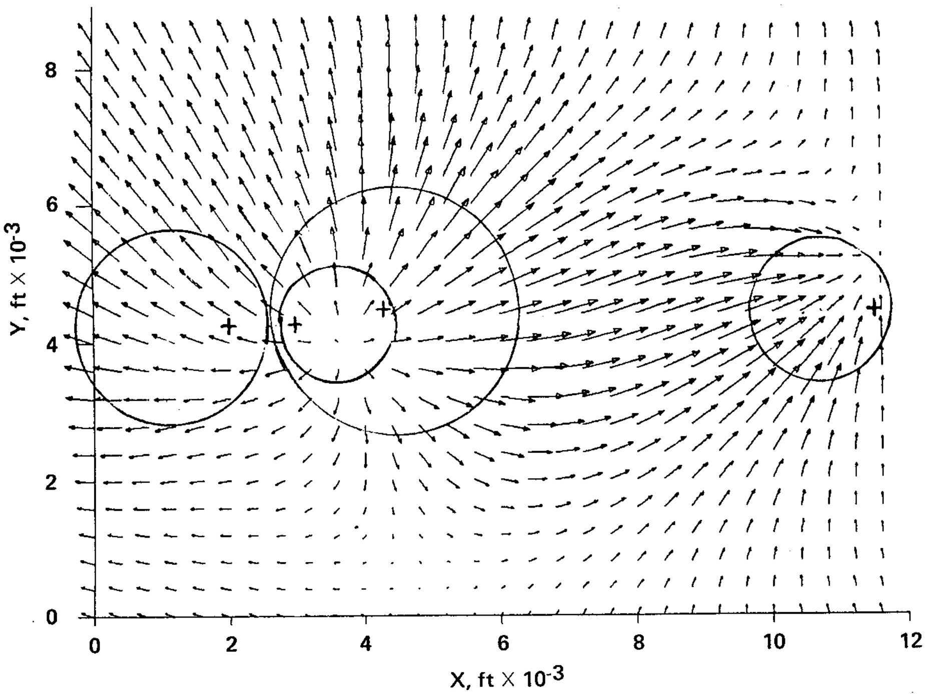


Figure 5.- Down-burst locations and horizontal flow field for JAWS match, H = 50 ft.

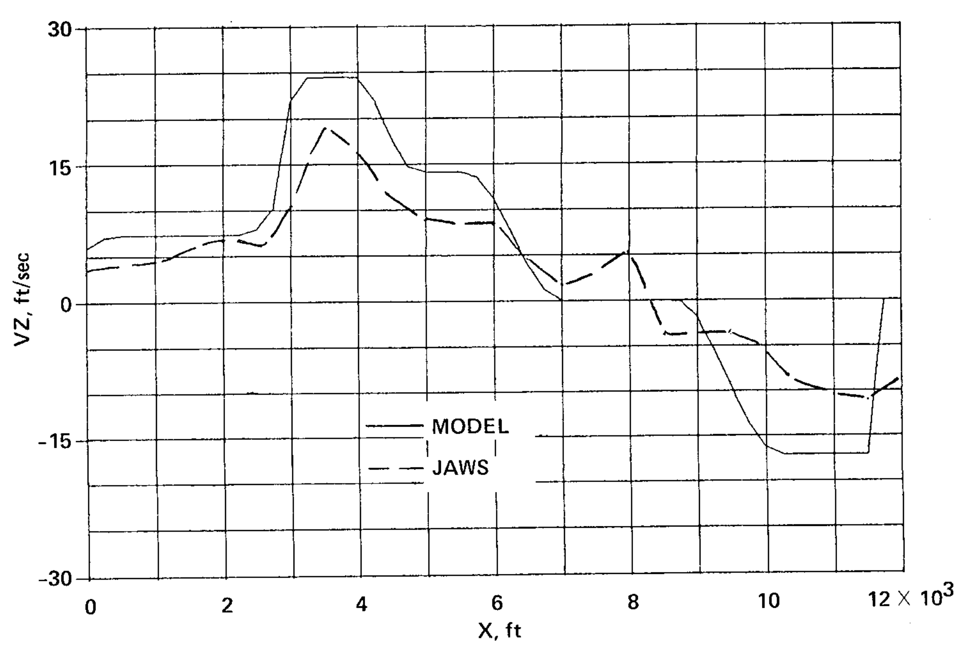


Figure 6.- Vertical winds, JAWS and model, H = 500 ft.

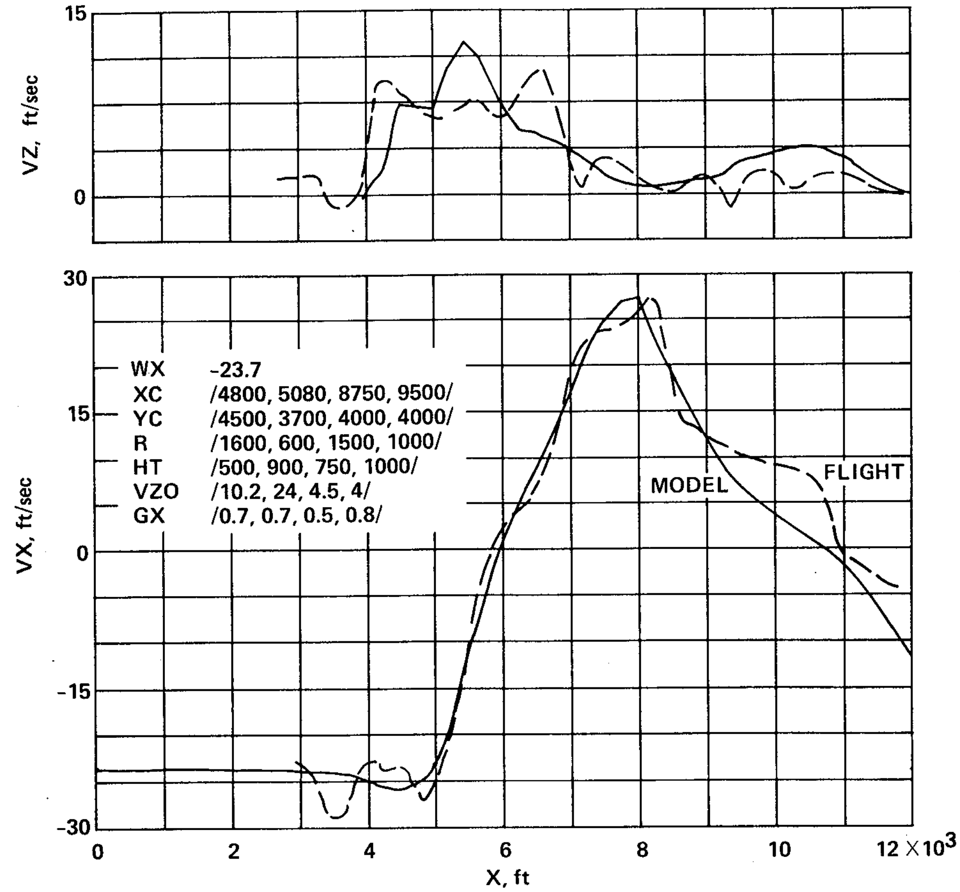


Figure 7.- Model of shear recorded in landing approach near-accident, 1975.

was made at such matching, although down-burst centers were offset from the nominal course line to create variability in the defined crosswind component. Since the dispersion center can be offset from the nominal course line by as much as 0.5 RA without significantly altering the along-course wind components, a significant range of crosswind profiles can be associated with a given along-course variation.

CONCLUDING REMARKS

This paper describes a format for the modeling of hazardous wind environments in flight simulation, but does not attempt the definition of models for specific simulation objectives. Either of the two examples illustrated here, appropriately located relative to the runway, might meet the user's needs; however, if a comprehensive exploration or demonstration of wind-shear hazards is the objective, additional scenarios are required. Perhaps the primary virtue of a computational wind program, compared to a "table look-up" model, is its flexibility. Systematic variations in the sequence and magnitudes of horizontal and vertical winds can be effected with modest changes of the input file data.

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Point of Contact: Richard Bray, Ames Research Center, MS 211-2, Moffett Field, CA 94035 (415) 965-6002 or FTS 448-6002

16. Abstract

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