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Establishing a Database for Flight in the Wakes of Structures

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The NASA Ames "Shipboard Simulator" seems to have been the sole serious attempt to model flight in the wake of a structure. This simulator is based on a faulty airwake database that was established with a uniform velocity profile and very low turbulence. The present study attempts to correct this situation by making three-dimensional hot-wire anemometer measurements of the airwake properties of a stationary 1/141-scale model ship in a simulated atmospheric boundary layer. The measurements included velocities, turbulence intensities, and spectra at 17 points along typical helicopter glide paths, within one ship-length of the touchdown location. These data provide a preliminary single-point database for simulation of helicopter flight in the wake of the real ship. The results for one path only are presented. In general, the velocities and the root mean square values of their fluctuations decrease as the ship is approached. No correlation is found with the database in the NASA simulator. There is some doubt about the accuracy of certain measurements close to the ship because of very low mean velocities.

Nomenclature

f = frequency
H = height of boundary layer
L = integral length scale
n = velocity profile exponent
S = spectral function
U = along-wind speed in Von Karman expression
u = longitudinal (along-wind) velocity component
v = transverse velocity component
w = vertical velocity component
x = along-wind coordinate (+ upwind)
y = transverse coordinate (+ to port)
z = vertical coordinate (+ upwards)
z_o = surface roughness length scale
σ = standard deviation of velocity fluctuations about the mean

Subscripts
a = measurement at the ship anemometer
i = 1, 2, or 3 for x, y, or z directions, respectively

I. Introduction

THE only serious attempt at realistic simulation of flight in the wake of a building or a ship is the NASA Ames "Shipboard Simulator." Up to the time of this writing, the author was unable to obtain information about any other simulator, even of a carrier, that had an airwake model. The NASA simulator is based on measurements made in the wakes of model ships exposed to a uniform, almost zero-level turbulence, flow. Because of the many adjustments required to the NASA model, in response to pilot feedback, this simulator cannot be described as veridical.

Simulation of aircraft flight in a turbulent atmosphere depends on the availability of suitable statistical velocity and other data for that environment. In the free atmosphere, this is usually not a problem, but in the wake of a structure such as a building or a ship, the situation is much more complex. Computational procedures that preserve the information about the spectral function and various correlations have not been developed to the point where they can be applied to a complex bluff body. The only alternative is to scale suitably the environment and structure to model size, make the appropriate measurements in the wake of the model and then rescale the results back to full size.

The need for such simulation is evident from the very high cost of, and huge testing backlog in, the determination of safe operating envelopes for helicopters in a ship environment by the Naval Air Test Center. The problem of flight in the vicinity of ships is usually called the "Dynamic Interface" problem. The poor aerodynamic design of the superstructures of even the most "modern" ships results in boxy configurations that give rise to highly turbulent flows that separate from the sharp edges and reattach in an intermittent manner, leaving recirculating zones that create havoc with slowly moving flexible helicopter blades. The result is a narrow wind-speed/direction-safe operating envelope that greatly limits the ability of helicopters to startup/shutdown the rotor blades or takeoff/land in this helicopter/ship interface. The major problems are involved at high wind/ship relative speeds, though on certain ships, problems arise with wind speeds as low as 8 m/s (15 kt).

A fairly detailed study of the dynamic interface that cites over a hundred references is given by Healey.[1] This effort examines in some detail the atmosphere, the motion of a ship and its simulation, the relevant bluff-body aerodynamics, and the then current (1987) state of simulation of the helicopter motion—there has been little change since that time. Reference 1 also describes several unsuccessful attempts to model the airwakes of ships. These efforts erroneously modeled the freestream flow to the ship with a uniform velocity profile and almost zero level turbulence. Such airflows represent ship-generated winds only. In contradistinction, a strong ambient wind of about 20 m/s (about 40 kt), blowing over a fully developed sea produces a sheared and highly turbulent boundary layer; for example, the turbulence intensity at about 10 m elevation is about 25 times the value of about 0.5% that is typical of an ordinary tunnel. Strong winds blowing toward buildings on land generate wakes much like those of stationary ships; the roughness of the land or the sea surface generates the shear and turbulence.

Nave[2] describes the development of turbulence models for simulating VSTOL aircraft in carrier and frigate wakes. These models were based on first-order filtering of white noise, which

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it was claimed represented an improvement in accuracy and simplicity relative to the previously used second-order system. Fortenbaugh[3,4] outlines the construction of the simulation; initially, the airwake measurements from a model of a frigate, which were taken along horizontal paths with a rake of seven hot-wire probes, were interpolated to provide the velocities, turbulence intensities, and spectral functions along typical landing glide paths. Nondimensional mean velocities and the turbulence intensites were formed with the (uniform) free-stream windspeed. These data, together with the spectral functions of the velocity fluctuations, were used to provide the input to the simulation. Implementation of the turbulence model was by means of the commonly-used filtered white noise source. The most recent effort, known to the author, is connection with this database was by Hanson,[5] who introduced an "improved" white-noise filtering process but, nevertheless, indicated the need to reduce the variances by up to 70% before realistic simulation can be obtained.

A single-point simulator model assumes that all of the turbulence acts at the center of gravity of the aircraft. Simulation of flight, based on single-point data, seems to be the norm and, despite the fact that models of distributed turbulence exist, no attempt seems to have been made to incorporate these into simulators. It seems that, for flight in the free atmosphere, such complexity generally is not required; however, it is likely that the very steep gradients that exist in the near-wakes of structures will require such a model for reasonable simulation of the flight there.

Holley and Bryson[6] show how a multipoint simulator model could be constructed; the atmospheric turbulence is assumed to act at five points distributed on the surface of the aircraft. These points were: near the nose, at the center of gravity, near the tail section, and one point each on the wings. It seems likely that this type of model could be applied to flight in the airwakes of structures but, if the velocity gradients are steep, relative to the aircraft size, more points may be necessary. This would also require the availability of knowledge of the coherences of the velocities in the wake, and it is very likely that such information could be obtained only by the experimental procedures outlined in the present paper and the use of a cluster of three-dimensional anemometers.

The present study reports on the establishment of a suitable wind-tunnel boundary layer to simulate a neutral atmospheric layer and the measurement with modern hot-wire anemometry of the necessary wake properties for simulation. Furthermore, the aim is to present the data in the same form as those already resident in the NASA simulator; hence, this dictates to a large degree how the data should be made nondimensional. No attempt is made to investigate the turbulence kinetic energy, dissipation rates, shear stresses, nor any of the other fine details of the airwake.

II. Full-Scale Freestream Conditions

Lucid introductions to the earth's atmosphere, from an engineering standpoint, appear in numerous works, e.g., Houbolt,[7] Panofsky,[8] and Davenport.[9] The high wind speeds relevant to the dynamic interface problem arise from storm centers far from the actual ship, and are called neutrally stratified by meteorologists.[8-10] In contrast to other stratifications, there are available, for this regime, many statistical data and empirical relationships, although there is some scatter in the data at low frequencies. The most complete source of such data seems to be the Engineering Sciences Data Unit (ESDU),[10] which, through numerous reports, analyzes and tabulates data from hundreds of sources.

The present effort focuses on the velocities, turbulence intensities, and spectral functions in the clean tunnel and along the three glide paths chosen.

The principal parameters of the freestream airflow toward the ship are 1) the mean windspeed, time-averaged over an appropriate scale; 2) the turbulence intensity; 3) the longitudinal (or integral) length scale of the turbulence; and 4) the spectral function of the turbulent velocity fluctuations. Empirical relationships are available (ESDU data items 74030, 74031) for the above four parameters as a function of the mean windspeed, elevation, and roughness length scale.

Davenport[9] gives the range of $0.01 > z_o > 0.001$ for the roughness length scale in neutrally buoyant flow over the rough sea. The windspeed, as a function of height, is most commonly expressed as

$$u/u_{\text{ref}} = (z/z_{\text{ref}})^n \tag{1}$$

where u_{ref} is the known velocity at a specified reference level z_{ref}. The value of z is that above an "average obstruction" height; i.e., the mean wave height is used as the datum. A known ship anemometer reading gives the necessary profile, when the index n is known. According to Davenport,[9] this index is usually found by matching the log- and power-law profiles at some appropriate elevation, yielding

$$n = 1/\ell n(z_{\text{ref}}/z_o) \tag{2}$$

The most appropriate reference elevation for the present problem is a typical helideck height of 10 m (33 ft); then the above range of z_o values yield the range $0.1 < n < 0.14$. The turbulence intensity levels are given as a function of elevation and roughness in ESDU data item 74031; at the 10 m elevation over rough sea, the intensity lies in the approximate range of 13–17%. The spectral functions most frequently used are the Von Karman and the Dryden forms: the former is given by

$$fS_i(f)/\sigma_i^2 = 4(fL_i/U)/[1 + 70.8(fL_i/U)^2]^{5/6} \tag{3}$$

for the longitudinal direction, where $i = 1$ and

$$\sigma_i = \int_0^\infty S_i(f)\,\mathrm{d}f \tag{4}$$

The major role of the Dryden seems to lie in simulations.

The theory of isotropic turbulence predicts that the spectra for the two orthogonal transverse directions are related to the longitudinal spectrum through the differential equation

$$S_j(f) = \frac{1}{2}\left(S_i(f) - f\frac{\mathrm{d}S_1}{\mathrm{d}f}\right) \tag{5}$$

where $j = 2$ or 3 for the y or z directions, respectively.[11] In the atmospheric boundary layer, especially near the ground, the vertical scale is usually less than the horizontal scale of the turbulence. This difference in scale creates a vertical asymmetry leading to a preferred orientation of the eddies and giving rise to an inherently anisotropic condition that manifests itself as a quadrature component in the spectra involving the components of fluctuating velocity. In the vertical direction, where there is a strong asymmetry, the quadrature spectrum is significant, and the maximum correlation in the fluctuating horizontal wind speed at two different heights occurs not simultaneously but when the fluctuating velocity signal from the upper point is delayed by a time interval roughly equal to $\Delta z/\bar{V}_w$, where Δz is the height separation and $\bar{V}_w$ is the mean-wind velocity.[12]

The maximum relative windspeed for which helicopter/ship operations are likely to be conducted is about 25 m/s (50 kt) and this value is taken as a worst-case scenario. The greater the contribution of the ship speed to this value, the lower the turbulence intensity in the resulting freestream flow, because freestream turbulence does not accompany ship motion by definition. The distribution of the windspeed fluctuation in the atmosphere is known to deviate somewhat from the Gaussian; intermittency in the flow seems to account for most of this deviation. This is a factor that cannot be modeled correctly in wind tunnels.

III. Model Freestream Conditions

There are several ways in which modeling the atmospheric boundary layer in a wind tunnel can be achieved and they are discussed in Plate.[13] Recently, a sheared turbulent boundary layer, was established in a wind tunnel at the Naval Postgraduate School with a 1.5 × 1.5 m (60 × 60 in.) test section that is 6.5 m (20 ft) long; this layer simulates a neutral stability atmosphere over a fully developed sea. The method chosen involved a construction along the lines of Counihan's work.[14] A layer thickness was chosen that is much thicker (0.75 m, 30 in.) than the height of the deck of any ship model likely to be used. The factor for the current study was about 10. For this boundary layer to represent the atmosphere, the nondimensional velocity profile as a function of elevation must match in both tunnel and environment. The turbulence intensity profiles, spectral functions of the turbulent velocity fluctuations and the length scales should match also.

Figure 1 shows the mean of the nondimensional mean velocities across the test section as a function of nondimensional distance from the tunnel floor, with the velocity at the top of the layer (0.75 m) being 2.92 m/s. The maximum variance in the velocity values across the test section was 0.05 m/s above 150 mm (6 in.) and 0.025 m/s below that. A least-squares fit to the data indicated a value of the index n of 0.11, which is within the required range; the curve shown in Fig. 1 is for this value of n.

The mean of the turbulence intensities across the test section is shown in Fig. 2, together with the ESDU envelopes corresponding to z_o = 0.001, on the left, and z_o = 0.01, on the right. Only the highest and lowest data points lie outside the envelope. The influence of the slightly low value of the upper reading is expected to be negligible; it is far above the ship elevation. Meroney[15] in a recent review of the literature indicates that the primary influence of turbulence intensity on the shear layers is to increase their curvature and shorten the reattachment distance. Because the lowest point is just outside the envelope, it is likely to lead to insignificant changes in the flowfield, especially because the freestream impinges directly, to a minor degree only, on the shear layers at the relatively small 30 deg yaw.

The Von Karman spectral functions of the along-wind component of the velocity fluctuations, at helideck height, are shown in Fig. 3. The full-scale curve is shown on the left and the $\frac{1}{141}$ model-scale spectrum is shown on the right. The x marks around the model scale curve represent measurements in the wind-tunnel freestream flow at helideck height with a clean tunnel, and the agreement is quite satisfactory.

Autocorrelations of the along-wind velocity components were obtained directly from time-delaying the signal at a number of elevations in the clean tunnel. These permitted estimates to be made of the integral length scales in the freestream flow, on the basis of Taylor's frozen-turbulence hypothesis, and the ratio of these scales to the boundary-layer thickness are denoted by x marks in Fig. 4.

Robins[16] compared the ratios of the estimated length scale to the boundary-layer thickness for artificial layers and for the natural one and found similar values. Taking the 75 mm point, which is 10% of the layer thickness in the wind tunnel, and closely the helideck elevation, the estimated integral length scale was 231 mm, which represents 231/750 = 31% of the thickness of the artificial layer. The thickness of the natural layer is difficult to quantify, but is often taken (ESDU, for example) as 600 m. At 10% of this, 60 m, the ESDU data sheet gives a length scale 160 m approximately or 34% of 600 m. Robins gives a range of length scales from 15% to about 35% of the boundary-layer thickness of the 10% elevation.

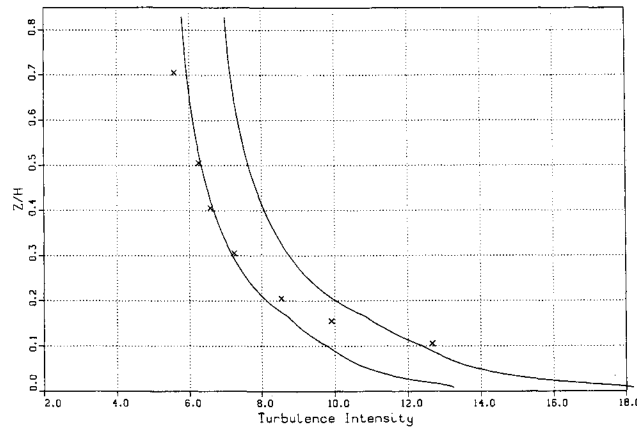

Fig. 2 The mean turbulence intensity in percent across tunnel.

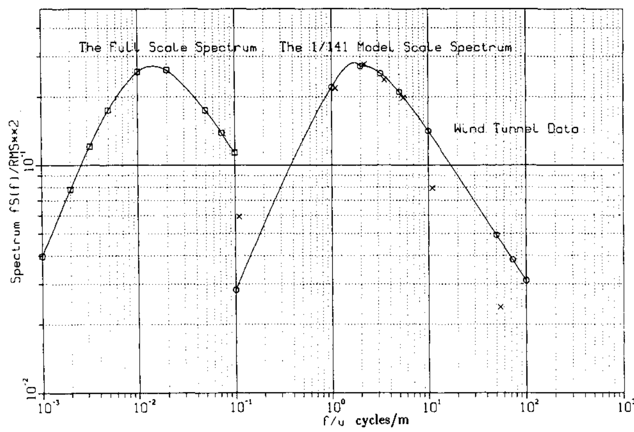

Fig. 3 Comparison of velocity spectra with Von Karman.

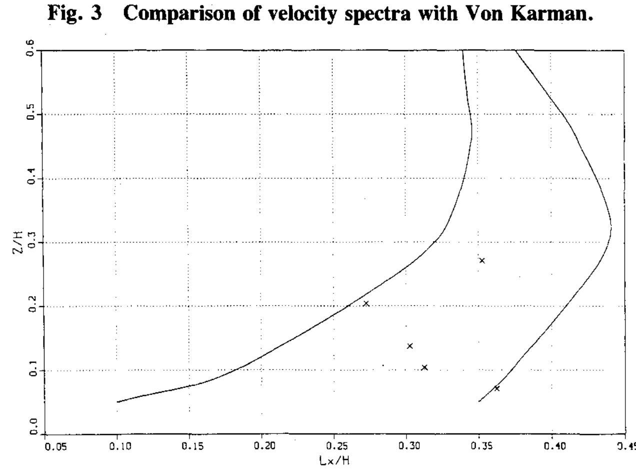

Fig. 4 Integral length scales in tunnel.

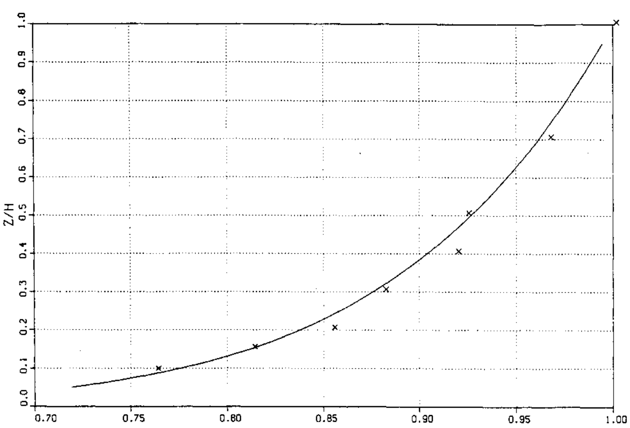

Fig. 1 The mean velocity profile u/u_∞ across tunnel.

All of the estimated length scales from the tunnel measurements lie within the envelope of Counihan's data (Ref. 14, p. 583), which is also shown in Fig. 4.

In conclusion, it is believed that a sufficiently close matching of the neutrally buoyant atmospheric layer and the simulated boundary layer in the tunnel has been achieved.

IV. Wakes of Structures

Because buildings and most ships that are considered stationary have geometries and airwakes that have much in common, the article by Cermak[17] makes a useful contribution. (Further discussions appear in Refs. 1, 9, 13, and 15.) An important assumption made in the construction of the NASA simulator model is that the airwake moves with the ship; this was necessary because the airwake database was established with a stationary ship model. Hence, for compatibility with this existing simulator model, it is desirable that the data be taken with a stationary ship model.

Whether with tall buildings or ships, one inevitably has to deal with boxy-type structures, with sharp edges and highly turbulent recirculating flows in their wakes. Johns and Healey[18] studied the broader aspects of the flow over a ship flight-deck, which was located aft of a box-shaped hangar. In a zero-yaw wind, the flow over the hangar/flight deck combination, along the centerline of the ship, showed the characteristics of a turbulent flow over a backward-facing step. The familiar, highly turbulent recirculation was present. Near the edges of the ship, however, the flow was much more complex; there, the air flowed on both sides and these streams joined the forward flow along the centerline (the recirculation) and all flowed up the rear hangar face. A much more detailed study was carried out by Rhoades and Healey[19] with a view to determining the origin of flows that caused helicopter blade strikes.

These highly turbulent recirculating flows have very serious consequences both for the measurement process and for the operation of the flight vehicles in these wakes. Ships other than carriers are usually classified as nonaviation, and in the past decade naval operations have come to rely heavily upon the use of helicopters in conjunction with such ships. It seems to be a common procedure for all navies to map the safe operating envelopes for each helicopter/ship combination; these envelopes are bounded by the relative wind/ship speed velocity vector. Typical procedures are described by Carico et al.[20] and Hofman and Fang.[21]

V. Equipment and Measurement Parameters

The ship model was positioned on a turntable in the wind tunnel with a 1.8 m (6 ft) traverse positioned well downwind along the tunnel wall. This traverse was set at an angle of 4 deg to the horizontal, parallel to the axis of the tunnel and had a positional accuracy of $\frac{1}{12}$ mm/m. The triple probe was mounted on a arm that projected forward about 0.5 m (20 in.) from the mounting plate on the traverse, minimizing possible sources of interference flows.

The commercially available triple hot-wire probe, with a diameter of 9 μm, and a length of 1.25 mm was used to acquire the data. It was used in conjunction with a 20-to-1 bridge and constant temperature anemometer system. The data were passed to a 25 MHz computer via a 12 bit a/d board.

It was soon found that, successive sample sizes of about 8000/channel, taken at the same point in space, had too much variability. The sample size was gradually increased and at 65,536 the variability was down to about 1%. It was clear from these initial measurements that there was considerable energy in the low-frequency fluctuations in the flow. Experimentation with the sampling and the low-pass cut-off frequencies yielded a wide variety of spectra. In particular, sampling at frequencies of about 4 kHz or higher produced a spectrum that fell off with the Kolmogoroff-5/3 slope, showing the presence of a distinct inertial sublayer in the flow. However, sampling at such frequencies leads to shorter sampling times, which cannot resolve the lower frequency components in the turbulence. On the other hand, sampling at the 2 kHz achieves the latter, but displays a less pronounced inertial layer. The influence of this choice of sampling parameters on the simulation of flight in the wake is very much an open question. Preliminary measurements showed that the turbulent energy content in the flow at frequencies above about 1 kHz was about $\frac{1}{100}$ of that at lower frequencies. This offered guidance for the sampling rate and filter settings to avoid aliasing and reasonably limit the amount of processing. The final measurements were taken at 2 kHz per channel (32 s per channel), with the low-pass filter set at 1 kHz; this avoided unnecessary processing and aliasing. The spectra were averaged in blocks of 64 and windowing was not used.

VI. Experimental Procedure

The probe was calibrated in the velocity range of about 0.6–4 m/s (2–13 ft/s) at a turbulence intensity of about 4%. The reason for the low velocity is that the simulated layer was established with the intention of satisfying both the minimum Reynolds number for viscous/inertial similarity and the exact Strouhal number for modeling the dynamic motion of the ship. A freestream speed of about 3 m/s at the top of the boundary layer satisfies the minimum Reynolds number of about 11,000 and allows Strouhal modeling of the roll/heave/pitch of most ships. For the model used here, 1.5 m/s at helideck height adequately satisfied this criterion. A typical nonaviation ship operates at a maximum beam-based Reynolds number of 10^7–10^8 and, if the edges are sharp—as almost all are—the minimum figure of about 11,000 is adequate. In the present study, however, no ship motion is considered.

It is essential that the triple probe be oriented as precisely as possible in the tunnel and this was achieved to less than half a degree by using a transit. The probe was moved along straight-line trajectories that ended over the touch-down point of the flight deck. Data were collected at 17 sites that were uniformly spaced $\frac{1}{16}$ of a ship-length apart. The sites were listed by points, 0 over the touchdown point, 16 one ship-length away, or by percentages of a ship-length aft of the touchdown point on the flight deck. Three runs were made, each approaching the flight deck from aft. These were along paths that terminated at an elevation of 21 mm (closely, 3 m or 10 ft full-scale) above the touch-down point of the flight deck. Because of space limitations, the results of one run only are presented here. This run was straight upwind with the ship at 30 deg; i.e., the model was yawed 30 deg to starboard. The probe then was directed upwind in the positive x direction, the y axis pointing to port, and the z axis upward.

The single-point data taken include the mean velocity components, turbulence intensities, and spectral functions. All the velocity components were made nondimensional with the velocity u_a at ship anemometer height and the turbulence intensities were constructed with the same velocity. This is a reasonable procedure in that the velocity components at the corresponding points in the wake of a full-scale ship can be found immediately from the anemometer reading. The velocities and turbulence intensities in the existing database in the NASA simulator were made nondimensional, using the value of the uniform freestream velocity. In the present study, because the velocity varies with elevation, it is more appropriate to reference them to the value of the velocity at the ship anemometer. The use of the ship anemometer velocity in this definition of turbulence intensity, camouflages the fact that the local velocity components are very small at some locations along the glide path. Forming turbulence intensities with these local components would yield values of several hundred percent in places, well outside the range of accuracy of the hot-wire anemometer. Nevertheless, this practice is widespread in boundary-layer studies.

The spectral functions are presented in the form $fS_i(f)/\sigma_i^2$, where the subscript $i = 1, 2, 3$ refers to the x, y, and z directions, respectively.

VII. Results

In the discussion below, the $x\%$ point refers to the data site at $x\%$ of one ship-length aft of the touch-down point. In addition, specific sites are labeled by point number as described in the last section. This is convenient because some data are presented as continuous; e.g., velocities and turbulences and some for specific sites such as the spectra. It is assumed that the starting point of the run is one ship-length away and that the end is over the touch-down point. The 30-deg position only is discussed.

The along-wind velocity component for this 30-deg starboard yaw, is given in Fig. 5. The nondimensional value drops fairly smoothly from a maximum of about 80% to about one-half of this over the flight deck. The transverse and vertical components are shown in Fig. 6. It seems that the starboard yaw deflects the transverse flow slightly in the port direction. There is a gradual decrease in the velocity from a maximum of about 6% of the anemometer reading to zero over the deck. The vertical velocity is directed initially downward at about 12% of the anemometer reading. It then gradually decreases to zero at about the 40% point, after which it becomes an upflow and reaches a maximum value of about 10% of the anemometer values at about the 15% point. Thereafter, the value plummets steeply to zero over the deck. This rising and dropping flow is very characteristic of the flow over yawed ships, the downflow in the wake usually being called the "burble."

The velocity histograms, which are not shown, displayed a strong Gaussian character at points at least one quarter of a ship-length away. Near the model, they were considerably distorted, frequently having a central spike with very asymmetric tails.

All three turbulence intensities are shown in Fig. 7; the general pattern begins with higher intensities than the zero-yaw case—around 10%—followed by a slight rise and then a fairly steep fall to about 6–7%. This is followed by a steep rise to about 7–9%, and a final fall to around 4–5% over the deck. The spectra for this 30-deg run appear in Figs. 8–10.

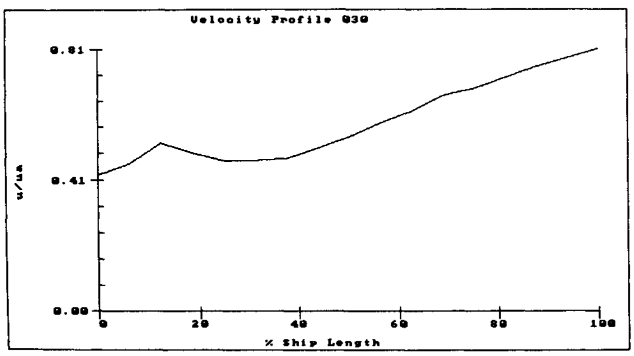

Fig. 5 Along-wind velocity profile 030 deg.

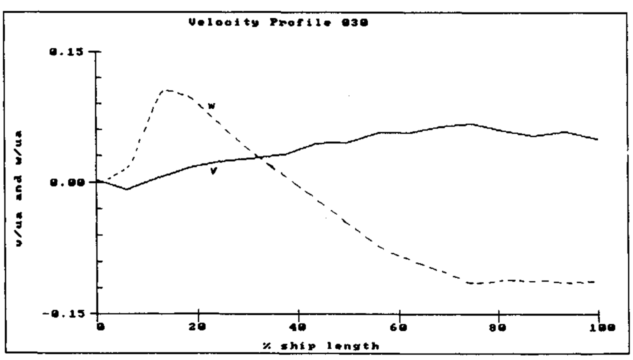

Fig. 6 Transverse and vertical velocity profiles 030 deg.

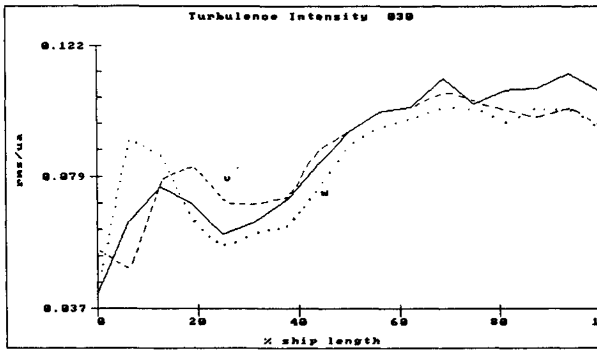

Fig. 7 Turbulence intensities 030 deg.

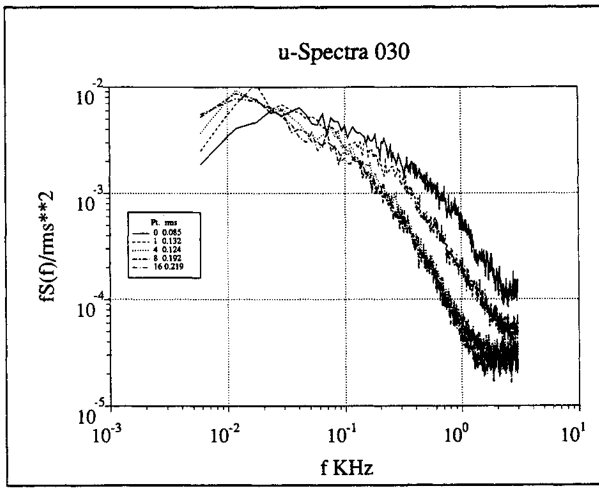

Fig. 8 Along-wind velocity spectrum 030 deg.

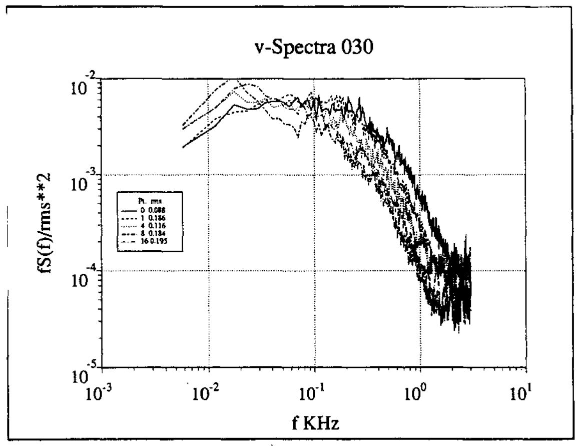

Fig. 9 Transverse velocity spectrum 030 deg.

As before, the graphs correspond to u, v, and w respectively and each figure shows the spectra for five sites, 0, 1, 4, 8, and 16. The substantial separations of the spectra on each figure show a velocity field that has been much more disturbed than for the zero-yaw case. The high-frequency end of Fig. 8 shows a sharp increase in the turbulent energy as the ship is approached. At 1 kHz the increase is by a factor of 10. This, however, decreases to zero at about 25 Hz and reverses at low frequency, i.e., there is less low-frequency energy over the deck than further aft in the wake. The v- and w-spectra in Figs. 9 and 10 display very similar characteristics.

VIII. Comparison of Present and Existing Database

An attempt was made to compare this database with that established by Fortenbaugh.[3,4] Reference 4 gives tables of

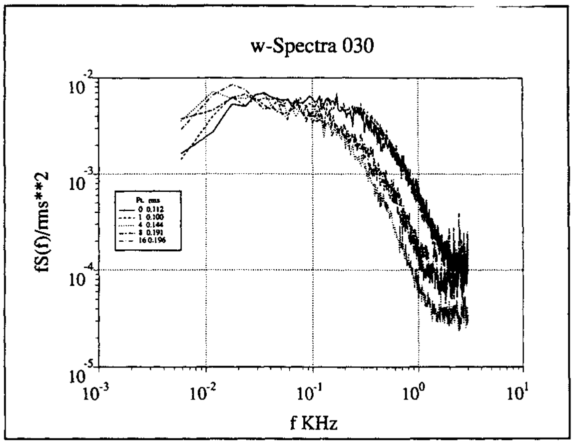

Fig. 10 Vertical velocity spectrum 030 deg.

velocities and turbulence intensities for the 30-deg case. In the graphs, Fortenbaugh has normalized the velocities and turbulences and somehow adjusted them so that the values are zero at a point far from the ship. It is easier to normalize the actual measurements given in his tables with the given 35 kt freestream speed and then to attempt to correlate the results with the values from the present study.

In general, little or no correlation was found. The three components of the velocities and turbulence intensities were extracted for a downwind line at an elevation of about 4.5 m (15 ft) off the deck, and normalized. The along-wind component of the velocity was indicated to have already reached 92% of the freestream value at $\frac{1}{8}$ of a ship-length aft of the touch-down point. In contrast, the present results indicate that only 80% is recovered at one ship-length aft. The greatest contrast is provided by the turbulence intensities, which are shown to increase as the ship is approached; whereas, the present results indicate the opposite.

IX. Conclusions

It is concluded that:

1) The neutrally buoyant atmospheric boundary layer is modeled adequately in the wind tunnel.

2) The database established here showed substantial disagreement with a previous one that yielded such poor fidelity of simulation. The previous database was constructed from measurements made in the wake of a model ship exposed to a uniform velocity profile and almost zero-level turbulence.

3) Despite some doubtful hot-wire measurements close to the ship, it is probable that a satisfactory database for single point simulation has been established. Because of very low mean velocities near the model, it is recommended that the measurements at the four points closest to the ship be retaken with a pulsed wire- or laser Doppler-anemometer.

Acknowledgments

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References

[1]Healey, J. V., "The Prospects for Simulating the Helicopter-Ship Interface," *Naval Engineers Journal,* Vol. 99, No. 2, 1987, pp. 45–63.

[2]Nave, R. L., "Development and Analysis of a CVA and a 1052 Class Fast Frigate Air Wake Model," Report: Airtask No. NF-41-400-000, P.E. No. 62241N, Naval Air Development Center, Warminster, PA.

[3]Fortenbaugh, R. L., "Mathematical Model for the Aircraft Operational Environment of DD-963 Class Ships," Vought Corp., Dallas, TX, Rept. N; 2-55800/8R-3500, 1978, p. 85, with 43 pp. of Appendix.

[4]Fortenbaugh, R. L., "Progress in Mathematical Modeling of the Aircraft Operational Environment of DD-963 Class Ships." AIAA Paper 79-1677, Boulder, CO, 1979.

[5]Hansen, G. T., "Airwake Analysis," Systems Technology, Inc., Working Paper 1198-3, Sept. 1983. Naval Air Development Center, Contract N62269-82-C-0728.

[6]Holley, W. E., and Bryson, A. E., Jr., "Wind Modeling and Lateral Control for Automatic Landing," *Journal of Spacecraft and Rockets,* Vol. 14, No. 2, 1977, pp. 65–92.

[7]Houbolt, J. C., "Atmospheric Turbulence," *AIAA Journal,* Vol. 11, No. 4, 1973, pp. 421–437.

[8]Panofsky, H. A., "Wind Structure in Strong Winds Below 150 m," *Wind Engineering,* Vol. 1, No. 2, 1977, pp. 91, 103.

[9]Davenport, A. G., *Engineering Meteorology,* edited by E. J. Plate, Elsevier, Amsterdam, The Netherlands, 1982, Chap. 12, pp. 527–569.

[10]ESDU Data Items 74030, 74031, Engineering Sciences Data Unit International, McLean, VA.

[11]Batchelor, G. K., "Theory of Homogeneous Turbulence," Cambridge Univ. Press, Cambridge, England, UK, 1953.

[12]Frost, W., Long, B. H., and Turner, R. E., "Engineering Handbook on the Atmospheric Environmental Guidelines for Use in Wind Turbine Generator Development," NASA TP-1359, 1978, pp. 4–94.

[13]Plate, E. J. (ed.), *Engineering Meteorology,* Elsevier, Amsterdam, The Netherlands, 1982, Ch. 13, pp. 527–569.

[14]Counihan, J., "An Improved Method of Simulating an Atmospheric Boundary Layer in a Wind Tunnel," *Atmospheric Environment,* Vol. 3, 1969, pp. 197–214.

[15]Meroney, R. N., "Wind Tunnel Modeling of the Flow about Bluff Bodies," *Journal of Wind Engineering and Industrial Aerodynamics,* Vol. 29, 1988, pp. 203–223.

[16]Robins, A. G., "Development and Structure of Simulated Neutrally Stable Atmospheric Boundary Layers," *Journal of Wind Engineering and Industrial Aerodynamics,* Vol. 4, pp. 71–100.

[17]Cermak, J., "Aerodynamics of Buildings," *Annual Review of Fluid Mechanics,* Vol. 8, 1976, pp. 75–106.

[18]Johns, M., and Healey, J. V., "The Airwake of a DD-963 Class Destroyer," *Naval Engineers Journal,* Vol. 101, No. 3, 1989, pp. 36–42.

[19]Rhoades, M. M., and Healey, J. V., "The Flight-Deck Aerodynamics of Non-Aviation Ships," *Journal of Aircraft* (to be published).

[20]Carico, D., McCallum, K. E., and Higman, J., "Dynamic Interface Flight Test and Simulation Limitations," *Eleventh European Rotorcraft Forum,* Paper 100, London, Sept. 1985.

[21]Hofman, C. F. G. M., and Fang, R., "Determination of Limitations for Helicopter Ship-Borne Operations," *Tenth European Rotorcraft Forum,* The Hague, The Netherlands, Aug. 1984.