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Project Summary

Evaluation of the Wake Effects on Plume Dispersion Using Video Image Analysis

Sarah A. Rajala and David S. Trotter

The full report summarizes results of a cooperative agreement. Video images of smoke flow in the wake of a model building were further analyzed in this research. Three projects were conducted. The first evaluated existing image analysis/ processing techniques to determine the contents of the data, develop a scheme for separating the smoke from the background, and determine the potential for analyzing the motion characteristics of the smoke flow. The second used the theory of fractals to extract information from the smoke images. These two projects identified a number of difficulties in characterizing smoke images. In the third project, a new technique for video imaging using laser sheet lighting was developed and tested. The resulting smoke images were more distinct and the noise levels were lower.

This Project Summary was developed by EPA's Atmospheric Research and Exposure Assessment Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction and Procedure

The Clean Air Act calls for regulations that specify the use of dispersion models in evaluating compliance with air quality standards. As a result, a special need exists for improved dispersion models to predict concentrations near sources that exhibit frequent building downwash problems. In addition, regulations on the design of "good engineering practice" stack heights require a better understanding of the extent of building wake effects. Until recently, researchers have obtained meteorological measurements and concentrations of air pollutants by sampling several fixed points over the spatial region and temporal period of interest. The recorded data have then been combined with available mathematical models to infer the overall pattern of pollutant concentrations for risk assessment Unfortunately, these limited measurements do not always provide all the information needed to adequately understand atmospheric processes under complex conditions, e.g., near buildings, mountainous terrain and/or for situations with chemically reacting pollutants.

One approach to improving dispersion models is to combine the traditionally obtained measurements with images of smoke to provide a visualization of the pattern of atmospheric transport. In fact, exploratory studies at the EPA Meteorology Division Fluid Modeling Facility in cooperation with North Carolina State University demonstrated the feasibility of using video sequence image analysis techniques for studying wake effects. From the results of this initial study, it was clear that further research was warranted to develop and evaluate techniques for recording, processing, and analyzing video image sequences of wake effects and to develop methodologies for utilizing this information to improve dispersion models. As a result, a cooperative research agreement (CR-813368) was established to continue this research.

To achieve the goals of this research, three topics were addressed. In the first two, we evaluated different approaches to analyzing the smoke flow data. Project 1 evaluated standard image processing techniques for analyzing the video image sequences. Project 2 explored the feasibility of using recent work on fractal theory to model and analyze the video image sequences. The results of the first two projects indicated a need for cleaner, more detailed imagery. We therefore decided that in Project 3, a laser-sheet lighting experiment for recording new video image sequence data would be designed and implemented. Projects 1 and 2 utilized video image sequence data collected at the EPA Meteorology Division Fluid Modeling Facility prior to this cooperative agreement. In the full report, we present the results from this agreement.

Results and Discussion

One characteristic of the image data we were interested in quantifying was the motion of the smoke, i.e., the time-varying changes in the image intensity values. Because of the nature of the smoke flow data, it was difficult or impossible to use existing motion analysis techniques. As a result, we approached the problem using two very different points of view. In the first case, we applied many of the traditional image processing/analysis techniques to assess the contents of the data, to develop a scheme for separating the smoke from the background, and ultimately to determine the potential for analyzing the motion characteristics of the smoke flow. The first set of image processing techniques we applied to the data were for determining its signal and noise characteristics. First, we displayed the individual bit planes of the digital image data in order to see if the least significant bits contained signal information or noise. Visually it appeared that the least significant bit plane contained only a random distribution of ones and zeros. To confirm this observation, we estimated the autocorrelation for the three least significant bit planes. The estimate of the autocorrelation for the least significant bit plane is approximately a unit impulse function. For bit planes 1 and 2 the autocorrelations become less like a unit impulse; there is correlation between adjacent pixel values. Thus, what we conclude is that a 7 bit binary representation is adequate to represent the signal information contained in this image data. Alternatively, we can say that for each 8 bit pixel intensity there is approximately 1 bit of random error. Another interpretation is that these data have a signal-to-noise ratio no greater than 42 dB. This is based on the rule-of-thumb that there is approximately a 6 dB increase in signal-to-noise ratio for each additional bit of information. This rule-of-thumb is based on the performance of a pulse code modulation (PCM) system with uniform quantization.

In order assess the spatial bandwidth of the image data, to determine whether the image data is likely to have aliasing due to spatial undersampling, and to visualize the noise, a discrete Fourier transform (DFT) of the image data was obtained next. The magnitude of the DFT of each image frame was displayed as an image, with the dynamic range of the data rescaled so that the largest value is assigned to 255 (white) and the smallest value to 0 (black). It is clear from these images that the image data has a low spatial bandwidth; that is, the data has been spatially oversampled (the highest frequency of the data is much less than the Nyquist frequency), so no aliasing is present. In addition, the intraframe noise was not a dominant factor even at the high frequencies.

Next, several linear and nonlinear image domain filtering techniques were applied to the image data to determine the feasibility of reducing what little noise was present. For the set of data we have processed, the spatial median filter provided the best technique for reducing unwanted intraframe noise and background artifacts without sacrificing the edge information in the images. In the temporal direction, a temporal low-pass filter yielded more reduction in interframe noise than did a temporal median filter. However, neither seemed warranted for this data.

The next set of image-processing techniques considered were the edge enhancement techniques. However, for the low contrast images in this data set, edge enhancement is not 0extremely beneficial, because the edge enhancement process also enhances the background. It should also be noted that the histograms of the edge enhanced data are different from those of the original data. If one chooses a histogram-based segmentation technique (see Section 3), it is useful to know if edge enhancement helps or hinders the segmentation process. In this case, it hinders more than it helps. We were interested in segmenting the image data into two pieces, smoke and background. To do this, it is useful to have bimodal histograms.

Edge enhancement on this data tends to make the histograms trimodal. This leads one to believe that the data should be separated into three classes. The question is what three classes? If it were smoke, dark background, and grid work, this might be useful. However, because the range of intensity values for the grid work overlaps with the range of values for the smoke, it did not appear that this would be effective and was not tried. It should be noted, however, that the segmentation approach based on optimal thresholding described in section 3 could be generalized for trimodal histograms.

Gradient-based edge extraction techniques were evaluated next. Several gradient operators were applied to the smoke image data. The 3 x 3 gradient operators provided edges that were less sensitive to random fluctuations in the image data. Although it is difficult to extract any quantitative information about the motion of the smoke from these images, they may yield useful qualitative information about the smoke flow when viewed as a temporal sequence.

Since one of the objectives of this research was to find a way to extract motion characteristics from the data, we evaluated methods for segmenting the image data next. Two approaches were considered, global thresholding and optimal thresholding. From our experiments, we concluded that it is difficult to heuristically find a single global threshold that would segment this image data. However, we found that optimal thresholding provided us with a robust means for segmenting the image data into two regions. We calculated optimal thresholds for nine subimages for each frame of image data and found consistency from frame to frame. The segmented image data can provide useful qualitative insight about the outer boundary of the smoke dispersion when viewed as a sequence and has proven useful for estimating motion parameters.

A very simplistic approach to motion detection involves the subtraction of adjacent frames in a sequence of image data. The idea is that stationary objects will subtract out and leave pixel values of zero, and in areas where motion has occurred, there will be nonzero pixel values. A fundamental assumption of this method is that all the images are spatially registered from frame to frame. We performed first, second, and third-order differencing on the image data. We believe there is potential for obtaining qualitative insight when viewing the first-order difference images as a video sequence. Little insight was gained for this data from second and third-order differencing because of the amplification of interframe noise. Perhaps if a better means for suppressing the interframe noise were found, the second and third-order differencing would be more useful. Alternatively, if cleaner image data are recorded, all three difference sequences may prove to be useful both for qualitative and further quantitative assessment of the motion characteristics.

Assuming that the boundaries of the regions in the segmented image data reasonably describe regions containing the smoke, they can then be treated as an object with mass and area. The integrated optical density (IOD) is a measure of the mass contained in each thresholded image of smoke. This information was then used to calculate the center of mass for each of the thresholded images. This allowed us to track and estimate the motion of each segment from frame to frame. Changes in area and integrated optical density generally reveal the stages of smoke accumulation. An increase in area and optical density would imply the end of the cycle of smoke accumulation, and a decrease in area would be expected to follow. An increase in optical density and a decrease in area might imply that the smoke is beginning its cycle of accumulating.

The last image processing operation performed was an attempt to visualize the boundary deformation of the segmented image data from frame to frame. Using the thresholded images, the boundary of each image was extracted in a binary image. Only the points on the boundary contour have a nonzero pixel value. By overlaying these binary images, a comparison of the deformation of the boundaries over time may be made. At this time only a qualitative comparison has been made, but future work could consider the boundary deformation more quantitatively. Attributes of shape and size could be computed and compared. This same process could be performed inside the smoke to characterize the boundary between diffuse and more concentrated smoke. Further work in this area would possibly derive significant information about changes in concentration of the smoke.

In the second project, we used the theory of fractals for extracting information from the smoke dispersion. A new model based on fractal concepts was developed and applied to a sequence of video images of smoke plume dispersion. The new model provides some qualitative and quantitative interpretations of transient flows by utilizing several fractal parameters to determine the flow activity. The parameters used in this study were the horizontal fractal parameter, the vertical fractal parameter, and two higher-order fractal dimensions, the correlation and information dimensions. The results were related to the motion characteristics and plume concentration. The computed fractal parameters were tested for various sized windows and provided us with information about the spatial-temporal behavior of the smoke flow. The initial results appear to be promising, but further research is needed to collect and analyze a set of data that includes video imagery as well as output from other measurement systems, e.g., hot-wire anemometry or hydrocarbon tracer. As a part of this research project, a review of dimensionality measurements for chaotic dynamical systems was prepared.

In the third project, we designed and implemented an alternative approach for capturing the smoke flow image data. The image data recorded previously were captured under flood lighting conditions. As a result, the two-dimensional image data was a projection of the three-dimensional volume of smoke flow onto a two-dimensional image plane. In the new system, laser-sheet lighting was used to generate a plane of illumination. Hence, we could selectively illuminate planar surfaces in the three-dimensional volume of smoke flow. Data were collected for various planar sheets of light generated by both a rotating polygonal mirror and a fixed lens configuration. Because these data were collected in the last six months of the research agreement, only preliminary evaluations on their usability have been performed. In the preliminary analysis, we found that the images gave clearer, more detailed data for analysis. The next step should be to apply techniques tested in Projects 1 and 2 using the new data.

Summary and Conclusions

We estimated basic motion characteristics of the centroid of the segmented image data. The approaches examined were simple and no constraints had to be employed regarding the linearity of the motion. The image data files analyzed in the major portion of this research were collected using flood illumination. Hence, the motion information extracted was for 3-D smoke flow data projected onto a 2-D image plane. Information that cannot be recovered is lost in this projection. Future work should include extending the motion estimation technique to include higher-order moments of the segmented image data and to applying this approach to the image data recently collected using the laser sheet lighting. In addition, other features of the image, such as correlations of the original image data, boundaries of segmented data, and intensity contours should be analyzed as a function of time.

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Sarah A. Rajala and David S. Trotter are with the Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC 27695-7911.
***Alan H. Huber** is the EPA Project Officer (see below).*
The complete report, entitled "Evaluation of the Wake Effects on Plume Dispersion Using Video Image Analysis," (Order No. PB 90-186 354/AS; Cost: $11.00, subject to change) will be available only from:
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650
The EPA Project Officer can be contacted at:
Atmospheric Research and Exposure Assessment Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

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