UNCLASSIFIED MASTER COPY - FOR REPRODUCTION PURPOSES

AD-A229 319

DTIC ELECTE OCT 26 1990 S B D

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) ARO 25014.8-EG
6a. NAME OF PERFORMING ORGANIZATION University of Illinois at Chicago	6b. OFFICE SYMBOL (If applicable)
7a. NAME OF MONITORING ORGANIZATION U. S. Army Research Office	
6c. ADDRESS (City, State, and ZIP Code) P.O. Box 4348 Chicago, IL 60680	7b. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211
8a. NAME OF FUNDING/SPONSORING ORGANIZATION U. S. Army Research Office	8b. OFFICE SYMBOL (If applicable)
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAAL03-87-K-0098	
8c. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)

Interferometric Tomography of High-Speed Aerodynamic Flows

12. PERSONAL AUTHOR(S) Soyoung S. Cha

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 7/1/87 TO 6/30/90	August 31, 1990	9

16. SUPPLEMENTARY NOTATION The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

Flow visualization, interferometry, tomography, three-dimensional, high-speed aerodynamics

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Tomographic visualization of three-dimensional flow fields from multidirectional interferometric data has various advantages in its noninvasiveness and relatively high resolution and instantaneous capture of gross fields. The technique, however, encounters ill-posed problems: that is, incomplete projection, limited angular scanning, and insufficient nonuniform data. In the research, three typical methods have been developed for accurately reconstructing flow fields from severely limited data. First, a general method termed the complementary field method (CFM) has been developed in order to treat the all ill-posed problems in a unified manner. This iterative method can be combined with any direct reconstruction techniques. A special approach, which employs the CFM, has been formulated for discontinuous shock reconstruction arising in aerodynamics. Second, direct reconstruction techniques based on continuous local

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED

19. basis functions have been developed. These techniques, utilizing higher order approximation, demonstrate better reconstruction for continuous fields. Third, a variable grid technique has been developed to reflect intrinsic spatial resolution information contained in interferometric data. Test results demonstrate substantial error reduction when the CFM and an appropriate developed technique are coupled.

INTERFEROMETRIC TOMOGRAPHY OF HIGH-SPEED AERODYNAMIC FLOWS

Final Report

Prepared by Soyoung S. Cha
August 31, 1990

Submitted to U.S. Army Research Office
Contract Number: DAAL03-87-K-0098

Department of Mechanical Engineering
University of Illinois at Chicago

THE VIEW, OPINIONS, AND/OR FINDINGS CONTAINED IN THIS REPORT ARE THOSE OF THE AUTHOR(S) AND SHOULD NOT BE CONSTRUED AS AN OFFICIAL DEPARTMENT OF THE ARMY POSITION, POLICY, OR DECISION, UNLESS SO DESIGNATED BY OTHER DOCUMENTATION.

1. Statement of Problems Investigated

Interferometric tomography, that is, reconstruction of three-dimensional refractive-index fields from multidirectional optical pathlength integrals, has great potential as a powerful diagnostic tool in high-speed aerodynamics. The interferometric method is of great value in its instantaneous capture of a gross field and noninvasiveness. In the past, the interferometric reconstruction has been implemented by those methods in x-ray tomography; however, characteristics of these two fields are distinct.

The fields in high-speed aerodynamics are continuous except at a shock. Being sampled usually at bright and dark fringes, the original interferometric data are relatively sparse and nonuniform. Especially, near a shock, the sudden density change accompanies data loss due to high fringe density and refraction. In addition, interferometric reconstruction frequently encounter major difficulties because of severely limited projection data in most applications. In fluid flow measurements, physical constraints due to the experimental setup, which include test models and test-section enclosures, are frequently present. These restrict angular scanning or block a portion of the probing rays. The problems of incomplete projection and limited view angle thus occur. The adverse effects prohibit accurate reconstruction of object fields and thus limit practical applications. Accurate numerical reconstruction requires full information. The ill-posed data reconstruction is sensitive to noise and produces geometric distortions with various artifacts. In order to accurately reconstruct flow fields from ill-posed conditions, new techniques need to be developed, which incorporate the distinct features of the interferometric measurements.

2. Summary of Important Results

In the contract period, three typical new techniques were developed as outlined below. As mentioned, these techniques reflected peculiar aspects of interferometric tomographic flow measurements.

2.1 Complementary Field Method

A general reconstruction method, termed the complementary field method (CFM), was developed to deal with all ill-posed data problems in a unified manner. The developed method is based on successive estimation of the flow field and reconstruction of the corresponding complementary field which is the difference between the estimate and the exact field. Since the complementary field, which eventually converges to a null field in iteration, is reconstructed instead of the flow field, it can provide better reconstruction properties and less error energies. Imperfect inversion techniques, in addition to ill-posed data, contribute to reconstruction errors. The CFM can be employed to abate deficiencies associated with both measurement data and computational reconstruction techniques. Being iterative in mature, it can easily incorporate a priori information. In reconstructing a flow field, sometimes approximate information can be known; i.e., field shape, range of values, discontinuity, boundary, etc,. Even slight knowledge of the field or its transform can be efficiently utilized with the method. The developed method was tested through computer simulation of experiments, that is, numerical generation of ill-posed data and corresponding reconstruction. When no estimation of the fields is made in the initial iteration, the fields reconstructed by the CFM displayed gradual reductions in their maximum as well as average errors, which approached limiting values. On the contrary, the conventional methods reached an optimum estimate and then diverged. The test observations indicated the importance of the initial estimate in reducing reconstruction errors and expediting convergence. Maximum error reduction was substantial. Noticeable improvements occurred near the region where the fields obtained a local maximum. In real application, this region is usually of our interest. The test results of simple continuous fields were encouraging. The convergence of the method was stable but rather slow. It can be expedited by employing a large correction parameter in calculating a new estimate.

2.2 Shock Reconstruction

Accurate reconstruction of a shock requires dense sampling at the discontinuity in order to obtain high frequency components of the spatial variation. Due to the data loss or inaccuracy near a shock, as explained, interferograms may not produce adequate information to resolve the shock vicinity. Consequently, conventional reconstruction techniques are not appropriate for reconstruction of continuous flow fields involving a discontinuous shock. A new approach was formulated, which utilized the CFM to improve reconstruction accuracy of a locally discontinuous field. The method is based on the use of a priori information of the shock position to compensate for the deficiencies associated with computational techniques in reconstructing a discontinuous field and loss of information due to noise. In a test of a high-speed aerodynamic flow, the shock positions can be accurately assessed by surface-mounted transducers or other optical means. The computer simulation of experiments indicated that fairly accurate reconstruction can be achieved by the developed method. Error reduction was substantial in the badly defined shock vicinity as compared with conventional methods. The reconstruction resulted in fast stable convergence.

2.3 Continuous Local Basis Functions

Conventional methods have difficulties in accurately reconstructing a continuous flow field from sparsely and nonuniformly sampled interferometric data. Continuous fields can be best reconstructed by higher-order continuous local basis functions (CLBFs). Series-expansion techniques using higher-order CLBFs were developed for reconstruction of continuous fields. CLBFs, having support in a local region, allow precise continuous approximation of a field. The developed techniques demonstrated power of approximation, independence of basis functions, and efficiency in computing projection data. Power of approximation provides approximating accuracy and smoothness due to the continuity of basis functions up to higher-order derivatives. Overlapping of CLBFs ensures a sufficient degree of freedom to represent a field in a basis. The strong independence of the overlapping basis functions allows uniqueness in determining the coefficients in series expansion. It guarantees that a distinct pair of coefficients corresponds to a significantly different reconstruction. Efficiency for projection calculation enables repeated calculation of projection integrals of CLBFs in setting up linear algebraic equations to be accomplished with great simplicity. The CLBFs allow high reconstruction accuracy with a fewer number of series terms and minimal artifacts under ill-posed conditions and undersampling. Three types of CLBFs were formulated and tested. Being series expansion methods, they are applicable, directly or indirectly, to a broad range of ill-posed problems. Under full information, performances of all methods (conventional and CLBFs) were fairly comparable. However, as the degree of ill-posedness increased, the CLBF method outperformed conventional ones, especially the fixed grid method. The fixed grid method exhibits large errors despite the post-smoothing through interpolation. When noise was introduced, reconstruction errors increased with noise levels in all methods; however, the CLBFs were less susceptible to noise than other methods. The

CLBFs could be defined only in the region where information is available. They could thus produce a better-conditioned coefficient matrix than nonlocal basis functions, especially under the presence of a large opaque object.

The CLBF method was combined with the CFM and the reconstructions were compared with those from the convolution backprojection and CFM combination. Both combinations reduced reconstruction errors with the CFM incorporated. Under full information, reconstructions were comparable. The performance of the CLBF combination, however, became superior as the degree of limited data and the level of noise increased. Under severely limited-data conditions, the CFM reconstructions initially converged and then slowly diverged.

2.4 Variable Grid Method

Interferometric data under ill-posed conditions lead to nonuniform scanning of a field. This nonuniform scanning should provide nonuniform reconstruction resolution with greater accuracy in the region that rays scan more closely. In general, we are interested in the region with a large density gradient. This region, producing dense fringes, allow close sampling. In practice, some regions can be heavily scanned to extract more information. When the fixed grid method (FGM, a conventional method) is employed, a relatively large number of uniform data is required in order for individual grid elements to have a sufficient number of rays crossing through them. In this way, a well-behaved coefficient matrix can be formulated but it restricts the number of grid elements, especially under ill-posed conditions. This strategy thus limits the reconstruction resolution.

In the research, a series expansion method termed variable grid method (VGM) was developed to reflect the intrinsic spatial resolution information contained in the original measured data while producing a well-behaved coefficient matrix for a stable solution. The VGM employs nonuniform rectangular-pulse local basis functions. In the method, the bases of a field are adjusted so as an appropriate number of rays pass through each of them. This allows a reasonably uniform degree of redundancy to an individual coefficient in the linear algebraic equations. The resulting well-behaved matrix yields a stable solution of the coefficients. The algorithm enables the region of interest, scanned densely with probing rays, to contain fine local bases and thus to be reconstructed with higher resolution.

The following general interpretations can be drawn on the reconstruction result comparison between the VGM and FGM. For complete data, the performance of the two methods, including the number of bases, was fairly comparable. They produced the almost same number of the optimum bases. As the degree of ill-posedness (incomplete projection and limited view angle) increased, especially limited view angle, the VGM produced a large number of appropriately adjusted bases. This led finer resolution in the region of interest and thus less reconstruction errors. Maximum errors were reduced mostly in the areas with large field values or steep gradients. On the contrary, the FGM produced appreciable distortions in reconstruction. This is believed due to the ill-behaved coefficient matrix. Overall the VGM performance was better than that of the FGM under any circumstances. The VGM allowed higher reconstruction resolution and accuracy for a given number of series terms. It thus produced minimal artifacts even under ill-posed conditions and undersampling.

Finally, the VGM can be combined with the CFM for further performance enhancement. This combination needs to be tested and compared with other combinations.

3. List of Publications

S.S. Cha and H. Sun, "Complementary Field Method for Holographic Interferometric Reconstruction of Three-Dimensional Flow Fields in High-Speed Aerodynamics," SPIE Proceedings, Vol. 981, pp. 289-295, pp. 289-295 (1988).

S.S. Cha and H. Sun, "Interferometric Tomography of Continuous Fields with Incomplete Projections," Optics Letters, Vol. 14, No. 6, pp. 299-301 (1989).

H. Sun and S.S. Cha, "Continuous Local Basis Functions for Interferometric Reconstruction of Continuous Phase Objects," SPIE Proceedings, Vol. 1162, pp. 320-329 (1989).

S.S. Cha and H. Sun, "Complementary Field Method for Interferometric Tomographic Reconstruction of High Speed Aerodynamic Flows," Optical Engineering, Vol. 28, No. 11, pp. 1241-1246 (1989).

S.S. Cha and H. Sun, "Tomography for Reconstructing Continuous Fields from Ill-Posed Multidirectional Interferometric Data," Applied Optics, Vol. 29, No. 2, pp. 251-258 (1990).

D.J. Cha and S.S. Cha, "Interferometric Reconstruction of Three-Dimensional Flow-Fields through Natural Pixel Decomposition," AIAA Paper 90-1517, Seattle, Washington (1990).

4. List of Participating Scientific Personnel

Soyoung Stephen Cha, Associate Professor, Principal Investigator.

Hongwei Sun, Ph.D. Candidate, thesis defense scheduled in Fall, 1990.

Dong J. Cha, Ph.D. Candidate, thesis defense scheduled in Winter 1990.