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고속 홀로그래픽 간섭 계측기를 이용한 자동데이터 처리 통합전문가 시스템

주 원 종*

An Integrated Expert System for Automated Data Reduction in High-speed Holographic Interferometry

Won-Jong, Joo*

ABSTRACT

홀로그래픽 간섭계측기로터 나오는 영상 데이터를 해석하는 전문가시스템에 대하여 기술하였다. 그동안 간섭띠무늬(fringe)를 해석하는 방법들이 어느 정도의 자동화를 이룩하며 개발되어 왔다. 그러나, 복잡한 간섭띠무늬 패턴(fringe pattern) 및 심한 잡음이 생기게 되는 고속도 항공공학 분야 또는 실험기계공학 분야에서는 신뢰할 만한 자동화를 이룩하기가 매우 힘들었다. 현재 사용가능한 방법중에는 간섭띠무늬 추적, 위상전이, 푸리에 변환, 회귀분석 등이 있는데, 이들은 소음제거나 데이터 수정을 하는데 있어서 극히 국부적인 정보에만 의존하였다. 결과적으로, 특별히 심한 소음이 있는 경우, 부정확한 위상중첩이나 간섭띠무늬 순차배열문제에 부딪히게 되고 따라서 작업자의 수작업이 심각하게 필요하게 된다. 본 논문에서는 간섭띠무늬 추적방법의 자동화를 위한 새롭고 포괄적인, 규칙기반 전문가시스템에 대하여 기술하였다. 새로 개발된 전문가 시스템은 간섭띠무늬패턴에 대한 전체적인 또는 지연적인 정보를 추출해 내고 또 전문가가 가지고 있는 지식을 이용한다. 이 전문가 시스템은 저수준 및 고수준 처리를 동시에 할 수 있도록 상호연결기구를 채택하여 간섭띠무늬를 해석하는 적절한 해결책을 마련하였다. 또한 위상전이나 푸리에 변환 방법에서 문제가 되는 자동위상 중첩에 대해 개발된 전문가 시스템의 응용의 가능성에 대해서도 기술하였다.

Key Words : holography, interferometry, fringe analysis, expert system, image processing, hybrid processing, phase unwrapping

1. Introduction

Interferometry, an optical diagnostic technique which utilizes the interference property of coherent light, has made important contributions to accurate and reliable measurements in heat transfer, fluid mechanics, deformation studies, and adrodynamics[1, 2]. Interferometric methods have various advantages over conventional techniques. Their ability to instantaneously capture gross fields can negate tedious point-by-point measurements. Their nonintrusiveness is of great value in places where probe insertion is impractical because it would disrupt the field to be measured. The interferometric method can, in principle, produce both a high

* Dept. of Mechanical Engineering, Univ. of Illinois at Chicago, IL, USA

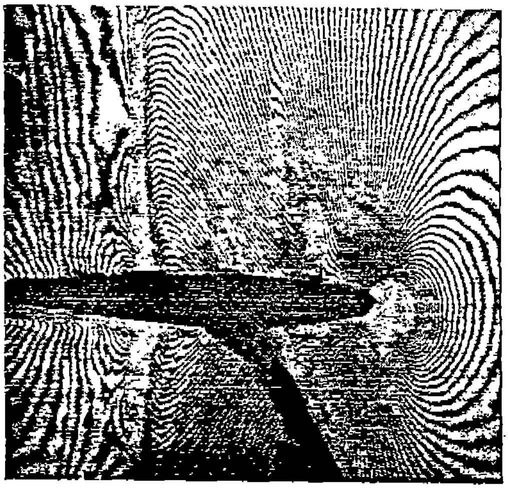


Fig. 1 A typical aerodynamic interferogram demonstrating noise effects

measurement accuracy on the order of a fraction of a wavelengh and good spatial resolution when compared with other techniques. Interferometric methods, however, frequently encounter various adverse conditions(3). The intensity variation of the laser beam causes uneven illumination and imperfect optical components can produce diffraction and speckle pattern due to the high coherence of the light. The long optical paths of probing rays can often be affected by ambient turbulence and vibration. Opaque objects can also block probing rays, causing ill-posed interferometric data. These noise effects coupled with a high fringe density usually inhibit accurate data acquisition. Figure 1 shows an example of noise-ridden interferometric images in high-speed aerodynamics.

In recent years, due to the rapid advances in computer and image processing technology, some practical techniques have developed for interferometric image analysis with limited degrees of automation. Currently popular techniques are fringe tracking, the Fourier transform, the phase shifting/heterodyne, and the regression methods(4). However, under the circumstance of complex noise-ridden fringe patterns, these techniques can still confront difficulties in application and phase-unwrapping these techniques can still confront difficulties in application and phase-unwrapping, requiring substantial manual interactive correction. Conventional approaches for reducing data noise or correcting extracted erroneous phase information have depended heavily on local information covered by a small mask. The fringe patterns and large-scale noise should not be interpreted by local information but by global and regional analysis.

In this paper, an integrated expert system is described, which utilizes both global and regional information of fringe patterns and makes use of experts' knowledge in correction processed data. The developed expert system combines, in a single package, the low-level processing involving algorithmic noise reduction and extraction of global/regional feature values with the high-level processing for furth noise reduction and phase retrieval based on knowledge-based global structure examination. It can thus have the potential to substantially eliminate operator interaction and be a foundation for a more efficient expert system with extended knowledge base for automated fringe analysis.

2. Holographic Interferometry

Holography is a technique for recording and reconstructing light waves by which a volumetric image can be reconstructed. This three-dimensional reconstruction is possible since holograms record information about both the amplitude and phase of the light diffracted by an object whereas photographic pictures just record the amplitude while the phase information is lost. In hologram recording, a singel coherent laser beam is divided into two beams : that is, the object beam which passes through the test field containing flow information and the reference beam which passes around the test field. When a reconstruction wave which is identical to the reference beam illuminates the hologram, the hologram produces the original object image by diffracting the reconstruction wave.

Holographic interferometry is similar to holography except that two object waves are holographically recorded in sequence(5). Figure 2 demonstrates an arrangement for producing an interferogram of a phase object. The interferogram of an "undisturbed" object wave and a reference wave is recorded on a holographic plate at the first exposure. For the second exposure, the same holographic plate first exposed to a "disturbed" object wave and to the reference wave. If the reference beam is a plane wave propagating at an angle θ to the normal of the plate, its complex amplitude is given by

$$U_r(x,y) = a_r \exp(\, i2\pi f_y y\,) \tag{1}$$

where a_r is the real amplitude of the wave and $f_y = \sin\theta/\lambda$. The complex amplitudes of the undisturbed and disturbed object waves are given respectively by

$$U_{01}(x,y) = a_{01}(x,y) \exp[\, -i\, \Phi(x,y)\,] \tag{2}$$

$$U_{02}(x,y) = a_{02}(x,y) \exp[\, -i\,(\, \Phi(x,y) + \Delta\Phi(x,y)\,)\,] \tag{3}$$

where $\Delta\Phi(x, y)$ is the phase difference due to a change of the object field and $a_{01}(x, y)$ and $a_{02}(x, y)$ are the real amplitudes of two object waves. The irradiance of the double exposures at the film plane is given by

$$\begin{aligned} I(x,y) &= |\, U_r + U_{01}|^2 + |\, U_r + U_{02}|^2 \\ &= 2\, a_r^2 + a_{01}^2 + a_{02}^2 + U_r^*(\, U_{01} + U_{02}) \\ &\quad + U_r(\, U_{01}^* + U_{02}^*) \end{aligned} \tag{4}$$

where *denotes complex conjugates. The amplitude transmittance of the developed film is

$$\begin{aligned} t(x,y) &= t_b + \beta\, I(x,y) \\ &= t_b + \beta\, [\, 2\, a_r^2 + a_{01}^2 + a_{02}^2 + U_r^* \\ &\quad (\, U_{01} + U_{02}) + U_r(\, U_{01}^* + U_{02}^*)\,] \end{aligned} \tag{5}$$

where t_b is the bias transmittance and β is a constant of proportionality. The term $t(x, y)$ is called a holographic interferogram. When the reconstruction wave which is same as the reference wave for simplicity, $U_c(x, y) = a_r \exp(i2\pi f_y y)$, illuminates the interferogram, the transmitted light is

$$\begin{aligned} U_t(x,y) &= t(x,y)\, U_c \\ &= [t_b + \beta(2\, a_r^2 + a_{01}^2 + a_{02}^2\,)]\, a_r \exp \\ &\quad (\, i2\pi f_y y\,) + a_r^2\, \beta(\, U_{01} + U_{02}) \\ &\quad + a_r^2\, \beta(\, U_{01}^* + U_{02}^*) \exp(\, i4\pi f_y y\,) \end{aligned} \tag{6}$$

The first term in Equation(6) is a part of the reconstruction beam which passes through the interferogram with some attenuation and modulation. The second term represents a diffractive wave which is a reconstructed original object wave. This wave forms a three-dimensional virtual image of the object which can be viewed by an observer or transformed into a real image by the use of a lens for the purpose of photographing or video-digitizing the reconstructed object image. The third term represents higher-order diffraction which contains the conjugate of the original image. It propagates higher-order diffraction which contains the conjugate of the original image. It propagates at an angle 2θ to the normal of the plate and is usually not visible. The irradiance of the reconstructed wave is proportional to

$$I_T(x,y) = |U_{01} + U_{02}|^2 = (U_{01} + U_{02})(U_{01}^* + U_{02}^*) = a_{01}^2 + a_{02}^2 + 2a_{01}a_{02}\cos[\Delta\Phi(x,y)]. \quad (7)$$

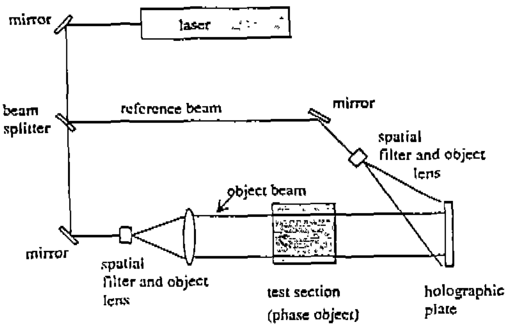


Fig. 2 Arrangement for producing an interferogram of a phase object

The superposition of the two wavefronts generates a two-dimensional sinusoidal interference pattern consisting of dark and bright fringes as shown in Equation (7) which is commonly expressed as.

$$I(x,y) = B(x,y) + A(x,y)\cos[\Phi(x,y)] \quad (8)$$

wher I, B, A, and Φ are measured intensity, background intensity, modulation amplitude, and interference phase, respectively. For interferogram reduction, the phase needs to be extracted from the intensity data obtained pixel by pixel. There exist a various interferogram reduction mothods. Current approaches can be classified into single-frame techniques based on fringe tracking, Fourier transform, and regression, and multiframe techniques based on phase-shifting[4, 6, 7]. As seen in Equation (8), the phase modulation $\cos\Phi$ is indeterministic. Fortunately, in general, the spatial frequencies of the background intensity and modulation amplitude fall below that of the phase

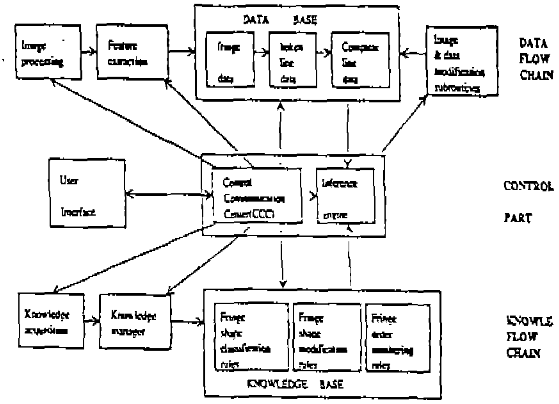


Fig. 3 Overall structure of the developed integrated expert system

modulation while that of noise exceeds all of these. Based on this premise, the phase modulation $\cos\Phi$ can be determined. However, the determination of the phase Φ still poses sign and 2π-ambiguity if no a priori knowledge is available. For multiframe approaches, providing sufficient number of measurements by varying the phase shift $\Delta\Phi_i$, the phase can be calculated under no restriction assumptions but still with 2π-ambiguity.

3. Stucture of Integrated Expert System

The meaning of the term integration used in "Integrated expet system" includes the cooperation of the traditional expert system with the conventional data processing system, other AI fields such as computer vision and natural language, and several fringe analysis techniques in a single package. Since there is no suitable off-the -shelf expert system for the analysis of noise-ridden interferometric images which require substantial image processing and knowledge manipuation, in this research a new expert system shell image processing and knowledge manipulation, in this research a new expert system shell is developed our purpose and a prototype knowledge base for high-speed aerodynamic interferogram analysis is developed for the test of the developed expert system shell.

To be a user-friendly, expandable, and speedy system, the processing modules of both the low-level and high-level processing for fringe analysis need to be sturctured hierarchically in a single package and also need to be programmed in a modular fashion. The hierarchy of the system has control part, user interface and two chains of information flow-one is data flow chain which generates data from the image and the other is knowledge flow chain which generates knowledge about image. Figure 3 shows overall structure of the developed integrated expert system and brief description is given as follows.

1) Image processing module-performs image reading preprocessing and segmentation. It upgrades the image by using filters and performs data reduction through thresholding and edge detection.

2) Feature extraction module-extracts necessary features from images which are first numeric values and then converted to symbolic codes to be evaluated in the high-level rule matching process.

3) Data base-is a short-term storage of feature data and processing information. It consists of three kinds of data groups-fringe data, broken line data, and complete line data.

4) Image and data modification subroutine module-is a package of subroutines which receives orders from the inference engine to modify the image or data when a rule is fired receives orders from the inference engine to modify the image or data when a rule is fired to take action.

5) Knowledge acquisition module-has two tools : rule editor and spell checker. The rule editor displays editiong formats on the screen so that end user or knowledge engineer just needs to follow it and type rules in the screen. The spell checker compares each word with key words pre-stored in the long-term storage and reports results to the user whether the spelling is correct or not.

6) Knowledge manager module-is a package of supporting facilities to help knowledge manager or end user to manage the knowledge base easily and efficiently. The knowledge rules and key words can be added, deleted, modified, reveiewed, saved, loaded, and printed at any time during the process.

7) Knowledge base-is a long-term storage of rules and keywords and consists of three kinds of rule groups-fringe shape classification rules, fringe shape modification rules, and fringe order numbering rules.

8) Control part-consists of two parts. One is Control and Communication Center(CCC) through which fringe analysis is performed under an overall strategy and the other is inference engine for pure inferencing. Inference engine is a reasoning machine which chooses appropriate rule base and data base to consider, and matches data with rules, and selects the rule to fire. Rule firing triggers image modification subroutine module to modify image or data.

9) User interface-provides a menu driven access to any module via CCC to interact with the system. This module gives a great flexibility to knowledge engineer or end user in managing the knowledge base as well as in analyzing the interferogram.

4. Interferogram Analysis and Results

4.1 Overall procedure

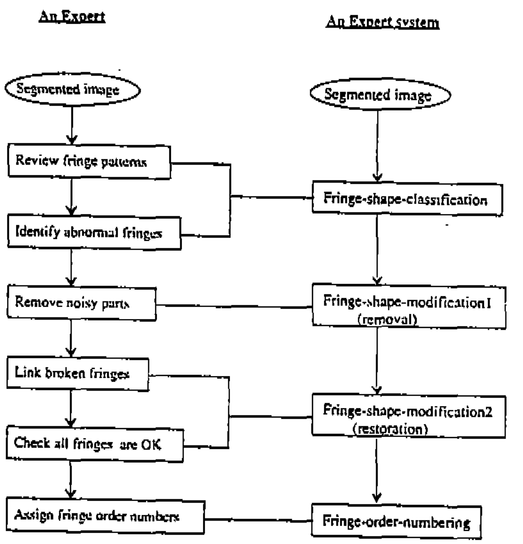


Fig. 4 Comparision of procedures between a human expert and the developed expert system

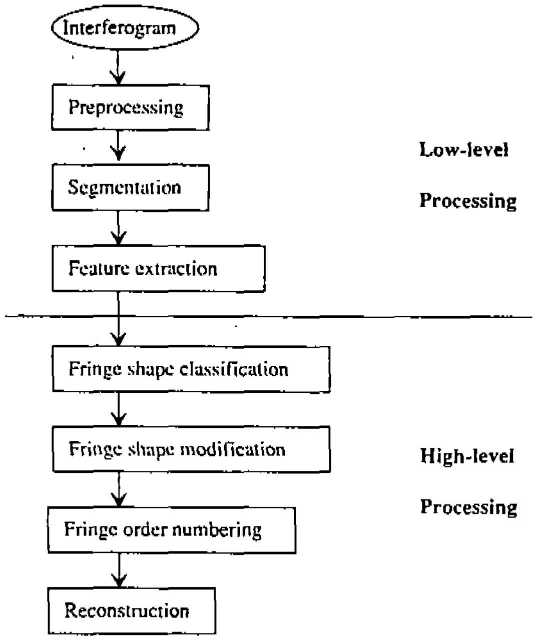


Fig. 5 Overall procedure of fringe analysis by the developed expert system

Fringe analysis can be described as a data reduction process that transforms two-dimensional interferometric images to isophase line data or unwrapped pointwise phase data. The developed expert system adopts a hybrid mechanism for low-level and high-level processing to produce an optimal solution in fringe analysis[8]. The system needs speed in numerical calculation as well as flexibility in managing the knowledge base. The low-level processing handles calculation-intensive algorithmic preprocessing for noise reduction, segmentation, and feature extraction. The noise reduction in the low-level processing, however, is strictly local and can be error-prone since the presence of noise may cause the local evidence to be misleading. Hence, integration with the flexible intelligent high-level processing is necessary for further noise reduction and fringe order numbering or phase unwrapping.

The high-level processing mimics the step-by-step process that a human expert might follow through coordination of his domain-specific knowledge and shown Figure 4. In the high-level processing fringes are first calssified according to their shapes. Abnormal fringes are then identified and modified based on a rule-matching process. After correction, fringe order numbers are assigned to all isophase lines through evaluation of their neighborhood relationship. The phase-map reconstruction or phase-unwrapping is then performed based on final isophase lines having fringe order numbers. Figure 5 shows the overall procedure of fringe analysis adopted by the developed integrated expert system. The expert system presented here has been developed primarily for gerodynamic interferometry. Consequently, the analysis examples and discussions will be given in this context.

4.2 Low-level processing

A digital image can be defined as image I(x,

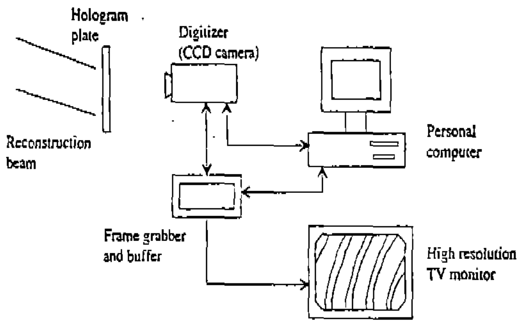


Fig. 6 Image reading facility for interferometric image analysis

y) which is discretized both in spatial coordinates and brightness. Through the image acquisition facility in image processing module as shown in Figure 6, an interferogram image is captured by a CCD camera (Pulnix TM-540) and uniformaly digitized by the frame grabber (Image Technology PC Vision Plus) in an array of 512×480 equally spaced samples. Each element of the array, often called a pixel, has discrete gray level values between 0 to 255 where zero is black and 255 is white. The digitized image is then stored in the storage module which is called a frame buffer.

Real interferometric holograms of high-speed aerodynamics usually have noises of uneven background, diffraction, speckle, varying contrast, broken of misconnected fringe, cloudlike fringe, etc[9]. The low-level processing consists of two sub-processing modules, that is, an image processing module and a feature extraction module. In the image processing module, interferometric images are preprocessed by applying an ordinary averaging median, high-pass, directional smoothing filters, of a combination of them. The ordinary averaging or median filter can reduce the fluctuation or speckle noise. The high-pass filter can eliminate uneven background noise by generating back-

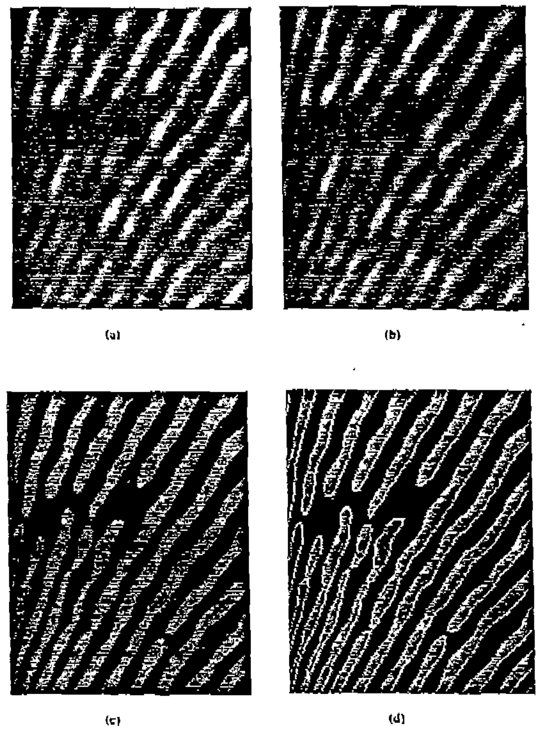


Fig. 7 Results of the low-level processing for a noise-ridden interferometric image in aerodynamic flow testing : (a) original image, (b) preprocessed image, (c) thresholded image, (d) edge detected image

ground map of whole image area and subtracting it original image. The directional smoothing filter enhances the directionality of fringe patterns which is one of most important information through out the analysis. Its importance and algorithm are well described in the reference[10]. The preprocessed images are then segmented for data reduction from pictorial pixel data to line-fringe data by applying variable thresholding and edge detection. Figure 7 shows the results of low-level processing for a noise-ridden interferometric image typical of aerodynamic flow testing.

Once line-fringe map is obtained in an image

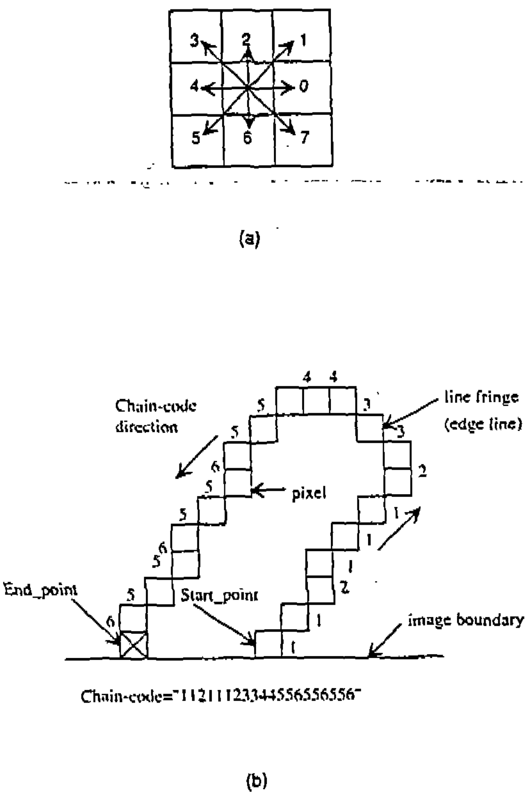


Fig. 8 Chain-code generation : (a) 3×3 mask of a scanner, (b) an example of chain-code

plane, fringe coordination is required for the quantitative data generation of the fringe information to be evaluated later. For this, chain-code system is adopted, which stores a sequence of directional information between adjacent pixels of a fringe. Chain-code is a string of octal codes representing a sequence of moves from the start-point to the end-point of a fringe. As shown is Figure 8, the 3×3 mask with 8 direction codes moves from one point to the next point along the dege in such a way that white region is located on its left. Therefore the chaincode of a line fringe possesses information of every pixel coordinates and its direction.

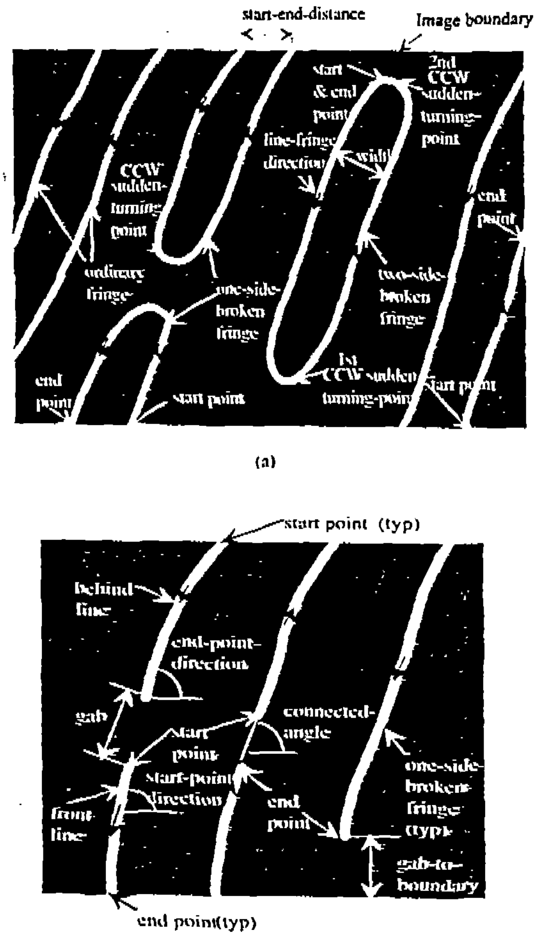


Fig. 9 Demonstration of feature parameters for (a) fringe data and (b) broken line data

In the feature extraction module, global/regional feature values are extracted from the segmented line fringes that have been generated. These feature values are used for examination of fringe patterns, i, e., broken lines, complete lines, etc., in the high-level processing as explained later. individual features represent simple data but combinations of thier pre-categorized ranges provide valuable domain-specific knowledge that can be utilized in the high-level rule-matching process[11]. That is, the extracted feature values are evaluated by knowledge rules for intelligent noise reduction and fringe numbering. Some examples of feature parameters given below and demonstrated in Fig. 9.

1) Length
2) Width
3) Start-end-distance : the straigh distance between two and points of a line fringe
4) Line-fringe-direction : the direction is chosen such that the fringe (bright region) is to its left
5) Sudden-turning-point (stp) : the location in a line fringe where the line-fringe-direction readily changes within a small interval. There are two types if directions, that is, counter clockwise (CCW) and clockwise (CW)
6) Gap : the straight distance between the neighboring end points of the two broken lines
7) Gap-to-boundary : the shortest distance from an end point of a broken line to the nearest image boundary
8) Direction-difference : the difference between the two end point directions
9) Connected-angle : the angle of an imaginary line connecting end points of two broken lines
10) Gap-angle-difference : the difference between the average of the two end point directions and the connected-angle

Cognitive studies have found evidence that human beings use only a small number of ranges to quantify facts of events in daily life. Since the expert system employs heuristics, rule of thumb, instead of numerical measurements, it has been suggested to transform the numerical values into a small number of qulifiers (i, e., very-low, low, medium, high, very-high) for describing the level of the data condition [11, 12].

4.3 High-level processing

In conventional fringe analysis programs, since knowledge is hidden in the control stucture or in an expert's braim, knowledge accumulation and standardization cannot be established in a systematic representation method. For utilzation of the expert system, knowledge should be separated from the control structure and be formulated in an explicit manner. Knowledge of an expert system can be represented in a number of ways. Rules are most popular since they provide a natural way of summarizing what is known. The advantages of using rules are modular coding, ease of understanding, and ease of tuning [13].

The low-level processing depends on local information. Consequently, it alone can not be self-sufficient for accurately evaluating noise-ridden interferograms in an efficient manner especially for phase unwrapping. To supplement this insufficiency, utilization of various a priori knowledge, i, e., aerodynamic interferometry, is required. Knowledge of experts can be classified into two categories. One is general knowledge which can be retrieved directly from interferograms and the other is the more domain-specific knowledge which is derived from the general knowledge and the processed images when fringe analysis is performed according to the methodology used in computer vision. Some of the general knowledge for defining characteristics fo fringe patterns can be as follows :

1) Origination/termination : no fringes terminate inside image boundaries including opaque objects except for loop-shaped fringes.
2) No crossing : no fringes intersect each other
3) Continuity : no fringes should be broken
4) Directionality : Most fringes are locally fairly linear
5) Similarity : adjacent fringes are similar and

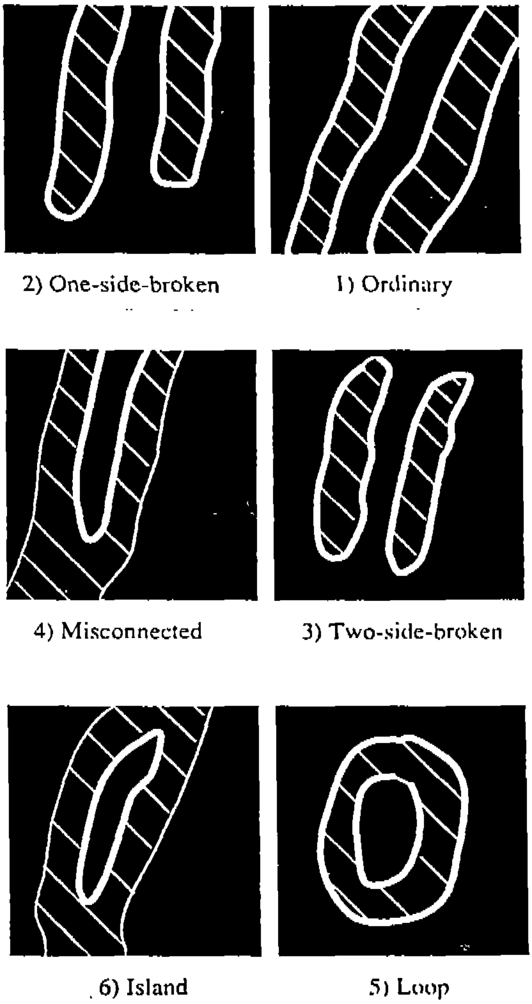


Fig. 10 Classification of typical fringe shapes (thick lines indicate the corresponding line friges)

almost parallel to each other

6) Locality : areas of severe noise are usually localized

7) Null closed-loop integration : when integrated over a closed curve, the sum of fringe order numbers becomes zero

The general knowledge needs to be reflected explicitly in the domain-specific knowledge rules in an expert system. Following table shows how the general knowledge is reflected in the knowledge rules in an explicit representation formula.

No.	General knowledge	Reflected by
1	orientation & termination	end-point type classification
2	no crossing	misconnected fringe identification
3	continuity	broken fringe identification
4	directionality	end-point direction calculation
5	similarity	neighbor fringe detection
6	locality	sudden-turning point detection
7	null close loop integration	continuous fringe order numbering

The high-level processing corrects noisy or incorrect fringe data presented by the low-level processing through thress consecutive processing stages, that is, frige shape classification, fringe shape modification, and fringe order numbering. The human visual cognition system, by mobilizing the general knowledge about fringe patterns, easily identifies which fringes are noise-ridden and which are acceptable as normal fringes. When fringe patterns in segmented edge-detected images are observed, typical fringe shapes can usually be found. If a computer can classify these fringe shapes by knowledge rules, it might be compatible to the human cognition mechanism. The main operation of the fringe shape which are commonly found in interferograms are described below and also depicted in Figure. 10.

1) Ordinary fringe : ordinary fringes start and terminate at image boundaries

2) One-side-broken fringe : one-side-broken fringes start at image boundaries, terminate inside image boundaries, and have a CCW sudden-truning-point

3) Two-side-broken fringe : two-side-broken fringes start and terminate inside image boundaries, and have two CCW sudden-turning-points

4) Misconnected fringe : misconnected fringes have a CW sudden-turning-point

5) Loop fringe : loop-shaped fringes have a zero start-end-distance and do not have a sudden-turning-point

6) Island fringe : isalnd fringes have two CW sudden-turning-points

The following is an example of fringe classification rules formed by a combination of the extracted features;

Rule name : fsc-rule
Rule no. : 500
IF : 1) length is not-low
2) start-end-distance is zero
3) no-of-stp is two
4) stp-direction is CCW
THEN : 1) fringe-shape is two-broken
Certainty : 0.8

Once all line fringes ard classified by their names, only abnormal line fringes remain in the processing domain for further analysis whereas the normal line fringes are registered in the complete line list(complete lines are isophase lines without defects). From this image, some important characteristics about the abnormal fringe patterns can be found as follows :

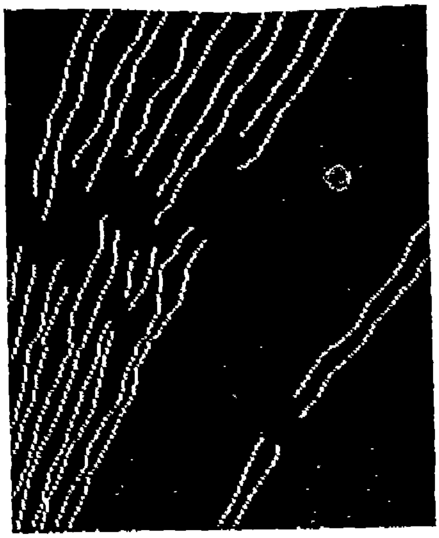
1) All abnormal fringes have at least one sudden-turning-point(Stp)
2) There usually exist other abnormal fringes in front of them as coupled partners
3) The direction of the Stp of an abnormal fringe is the same as that of the front partner
4) The gap distance between two abnormal partner fringes are unually small, etc

Therefore, the fringe shape modification processing needs to follow two steps : removal and restoration. The removal process splits abnormal fringe into broken lines by removing sudden-turning-points. The restoration process first searches for a partner line with a similar line-fringe-direction in front of or behind each broken line and then links them together through interpolation to complete the broken lines. The following are examples of fringe shape modification rules built from a combination of the extracted features :

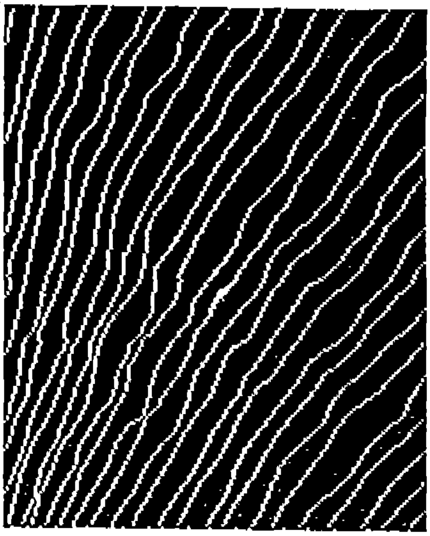
Rule name : fsm-rule
Rule no. : 200
IF : 1) fringe-shape is two-side-broken
THEN : 1) split fringe at Stp twice
2) register broken-lines in broken-line-database
Certainty : 1.0

Rule name : fsm-rule
Rule no. : 500
IF : 1) start-pt-type is OPEN
2) gap is very-low
3) direction-difference is low
4) gap-angle-difference is very-low
THEN : 1) partner-line is behind-line
Certainty : 0.8

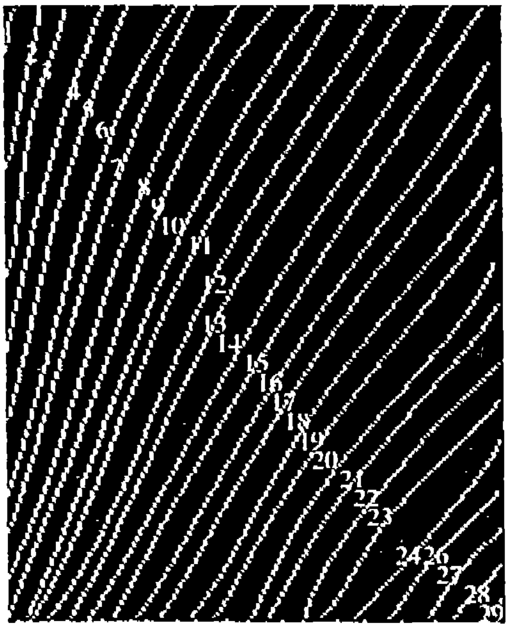
Rule name : fsm-rule
Rule no. : 900
IF : 1) partner-line is behind-line
THEN : 1) merge lines by backward-



(a)



(b)



(c)

Fig. 11 Results of the high-level processing : (a) broken line map, (b) completed line map, (c) final smoothed line map (isophase line map) with fringe numbers

extension
Certainty : 1.0

After fringe shape modification, all line fringes (complete lines) become noise-free and are stored in the complete line list. Some general knowledge such as similarity and null closed-loop integration can be reflected in fringe order numbering. Fringe order numbering can be interpreted as a process of establishing the overall neighborhood relationship of complete lines. The following is an example of fringe order numbering rules formulated by combining the extracted features :

Rule name : fsn-rule
Rule no. : 200
IF : 1) fringe-order-no does not exist
2) left-neighbor has fringe-order-no
3) order-direction is ascending
THEN : 1) increase fringe-order-no by one
Certainty : 1.0

Figure. 11 demonstrates the results of the high-level processing obtained from the data processed by the low-level processing demonstrated in Figure. 7. By applying the developed expert system to the fringe-tracking method, the large-scale noise which cannot be eliminated in the low-level processing is successfully corrected and the isophase lines are appropriately restored. However, its principle is equally applicable to other techiques including the Fourier transform or phase-shifting method as indicated earlier. In these techniques, usual phase unwrapping is based on simple pixel-by-pixel decision-making that checks sudden jumps between adjacent pixels. If errors exist in the search for sudden jumps due to a significant noise level or opaque objects, etc., the erroneous unwrapping propagates throughout the scanning, thus deteriorating neighboring unwrapped values(14). The proposed approach can perform phase unwrapping by regions(15). In the proposed method, an entire phase map can be divided into regions bounded by isophase lines. Through this processing areas affected by large-scale noise or blocked by opaque objects can be modified and restored. Since each region is clearly bounded by complete lines, there is no phase jump inside the region. The phase unwrapping can then be performed region by region by adding or subtracting the corresponding phase jump.

5. Conclusion

A PC-based expert system shell for automated interferometric image analysis was developed and tested with a prototype knowledge base for high-speed aerodynamic interferograms. In the developed expert system, the use of a fringe-tracking technique produced very plausible results even from a high-noise-level interferogram. The system provides a high potential to substantially reduce operator involvement. A new concept for regional phase unwrapping with the develpoed expert system is proposed. This approach can be a powerful tool in applying the phase-shifting and Fourier transform techniques. The low-level image processing upgrades images, performs data reduction, and extracts necessary features in the form of symbolic codes for the rule-based high-level processing. The high-level processing classifies fringe shapes, modifies abnormal fringes, and assigns fringe order numbers by intelligent rule-matching processing. The sepration of the knowledge from the control structure and the separation of the domain-dependent control part (CCC) from th pure inference as well as the use of the modular programming can promise an easy and secure expansion of the developed expert system shell and knowledge base.

Biogrphy

Wonjong Joo received his BS degree in mechanical engineering from Seoul National University in 1978 and MS degree in mechanical engineering from Korean Advanced Institute of Science and Technology in 1980, respectively. He was a research and supervising engineer at Hyundai Engineering Co., Inc. from 1980 to 1987. He received his Ph. D. in mechanical engineering at the University of Illinois at Chicago in 1993. His research activities are in optical diagnostics, phase-shifting interferometry, aerodynamic interferometry, and application of artificial intelligence to interferometry.

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