Optica Applicata, Vol. XXIX, No. 1–2, 1999

Application of the Fourier transform to fiber-optic sensor recognition

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The construction of the fiber-optic sensor of external perturbations and results of the relevant studies are presented. As a sensor head, the sample of two-mode optical fiber is used. Changes of intermodal interference condition, caused by external perturbation, generated changes of output speckle pattern. This output has been considered as an intensity image and diffraction method has been applied for its recognition. For this reason, the ring-wedge photodetector has been placed in the Fourier plane of the image studied. The digital signal generated by this detector has been processed by software neural network. As a result of a suitable process of network training, a possibility of recognizing the perturbation has emerged, which made it possible to avoid troublesome analysis of intermode interactions.

1. Introduction

The growing interest in fiber-optic sensors based on intermodal interference has been observed in recent years. The main advantage of such a solution is the possibility of obtaining the system sensitivity similar to that of the classical two-arm fiber-optic interferometric sensors for simple configuration of an optical part. The interference pattern obtained when coherent source illuminates a multimode fiber is familiar to many members of the fiber-optic sensing community. It is complex and random so that its usefulness for sensing technique is strongly limited. For dynamic signals, especially those which are coded in the frequency domain, multimode speckle has been used with some success as a crude sensing element [1]–[3] from data highways [1] to pressure [2] and strain measurement [3]. The potential applications of multimode speckle for static/quasi-static displacement measurements over relatively large ranges have also been presented by using the numerically calculated shape of the cross-correlation functions [4] and employing a neural network [5].

The main problems to be solved are efficient and reliable methods of recognizing the speckle pattern obtained in the above systems. The alternative method is an application of the quasi-monomode optical fiber. Then, by decreasing system sensitivity, a simpler speckle pattern is obtained. These patterns can be recognized in a simpler way by applying well-known signal processing methods used in fiber technique, *e.g.*, the four-detector technique.

In this paper, we discuss the possibility of using two-mode optical fiber with a new idea of credibility method of speckle pattern recognition. An output image from an optical fiber has been considered as an intensity image and diffraction method, known from automatic image recognition, has been applied for its recognition. For this reason, the ring-wedge photodetector (RWD), patented by ARC Inc., [6] has been placed in the Fourier plane of the image studied. The digital signal generated by this detector has been processed by software neural network. As a result of a suitable process of network training, a possibility of recognizing the perturbation emerged, owing to which a troublesome analysis of intermode interactions could be avoided. An additional advantage of this solution is the possibility of training the network in order to eliminate slow environmental perturbations.

2. Main idea of system work

The output pattern from a quasi-monomode optical fiber has the intensity distribution that depends on the number of interfering modes and the type of external perturbation interacting with the fiber. Each of the interfering modes can be identified through a mode number associated with a characteristic propagation constant and spatial distribution. Then intensity distribution at the output (Fig. 1) can be calculated as an interference sum of those modes [4]

$$I(r,\theta) = k \sum_{m=0}^{N} \sum_{l=0}^{N} A_l(r,\theta) A_m(r,\theta) \cos \Delta\varphi_{lm} \tag{1}$$

where: $A_l(r,\theta)$ is an amplitude of the mode l as a function of polar coordinates, r, θ at the fiber end, $\Delta\varphi_{lm}$ is the phase difference at the fiber end between modes, N is the number of modes in the structure and k is a constant.

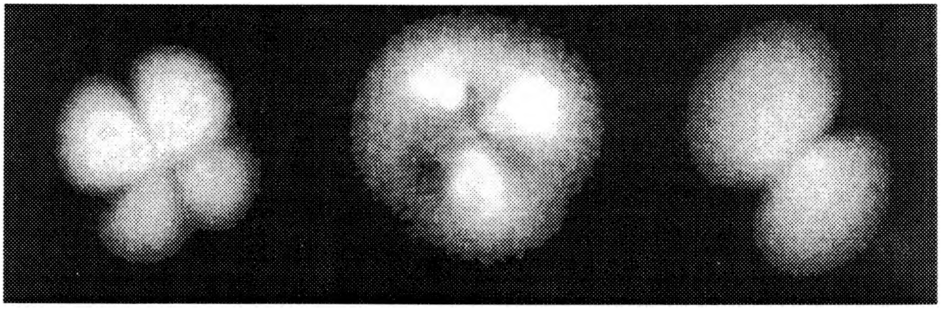

Fig. 1. Output images from four-, three-, and two-mode optical fibers.

The changes of the phase difference $\Delta\varphi_{lm}$ by any external perturbation cause changes in the speckle pattern. However, a direct identification of those changes is very complicated and some aforementioned methods must be used. In our approach, those images have been considered as intensity images and a diffraction method using RWD has been applied for their recognition. A short review providing motivation for our research is given below.

2.1. Main properties of the Fourier transform

The Fourier transform (FT) of a diffraction plane of an object includes distribution of the spatial frequencies present in the input object. In general, this transform is realized by optical lens in arrangement shown in Fig. 2. The distribution of spatial frequencies has many attractive properties, which allows efficient sampling of the

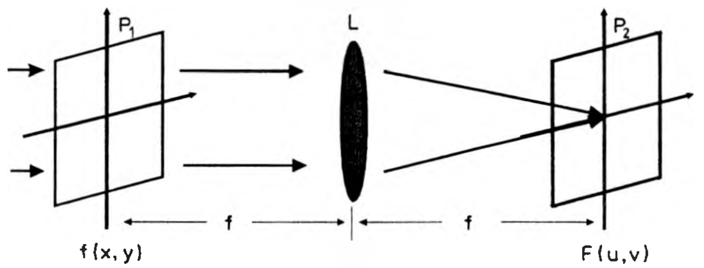

Fig. 2. Optical realization of the Fourier transform. P_1 – plane of input object, L – lens with focus f, P_2 – plane of the FT.

image. The first of them is its symmetric property, which offers a possibility of using information only from a half of the image plane. Because the intensity of the FT is also shift-invariant, then translations of the input images do not affect the magnitude of the Fourier coefficients. Hence, we see that the FT plane detector can be placed in the center of the FT plane and that each half of the FT plane can be sampled without loss of information. Another important feature of the FT pattern are rotational and scaling properties

$$|\mathcal{F}[f(x\cos\theta - y\sin\theta, x\sin\theta + y\cos\theta)]|^2 = |F(u\cos\theta - v\sin\theta, u\sin\theta + v\cos\theta)|^2, \quad (2)$$

$$|\mathcal{F}(f(ax, ay))]|^2 = |(1/a)^2 F(u/a, v/a)|^2, \quad (3)$$

which means that the dectector used can contain wedge- and ring-shaped elements [7].

2.2. Construction of detection system

The sampling of the FT pattern intensity in optical arrangement (Fig. 2) has been obtained by placing the speckle pattern in the plane P_1 and RWD in the plane P_2. The detector applied (Fig. 3**a**) has wedge-shaped elements in one-half of the circular aperture and ring-shaped elements in the other half. From the rotational feature (2), the FT pattern is seen to rotate as the input object rotates. Since the ring-shaped detector output is integrated over θ, the $f(r)$ ring-shaped detector output distribution does not change with input object rotations. From scaling property (3), the FT pattern is seen to scale inversely with changes in scale of the input object. Since the wedge-shaped detector output integrates over r, the $f(\theta)$ wedge-shaped detector output distribution does not change scale with input object scale changes. From (1), one can place the wedge-shaped detector elements in one-half of the FT plane and ring-shaped detector elements on the other half of the

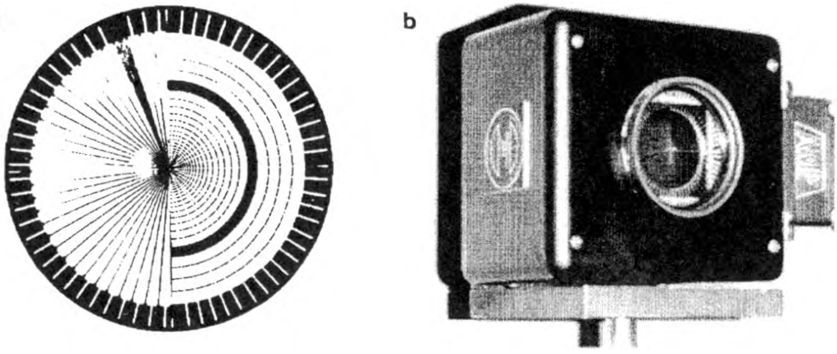

Fig. 3. Schematic (**a**) and general (**b**) view of RWD patented by ARC Inc. [6], [7].

FT plane, without loss of information. In the applied version of this device, there were 32 wedge- and 32 ring-shaped detector elements in each half of a silicon sensor of one-inch diameter (Fig. 3**b**). The 64 detector outputs are available in parallel and are fed through amplifiers into the IBM PC as 64-letter words. Each letter of the word has a value equal to the normalized intensity of a diffraction image in individual wedges and rings [8].

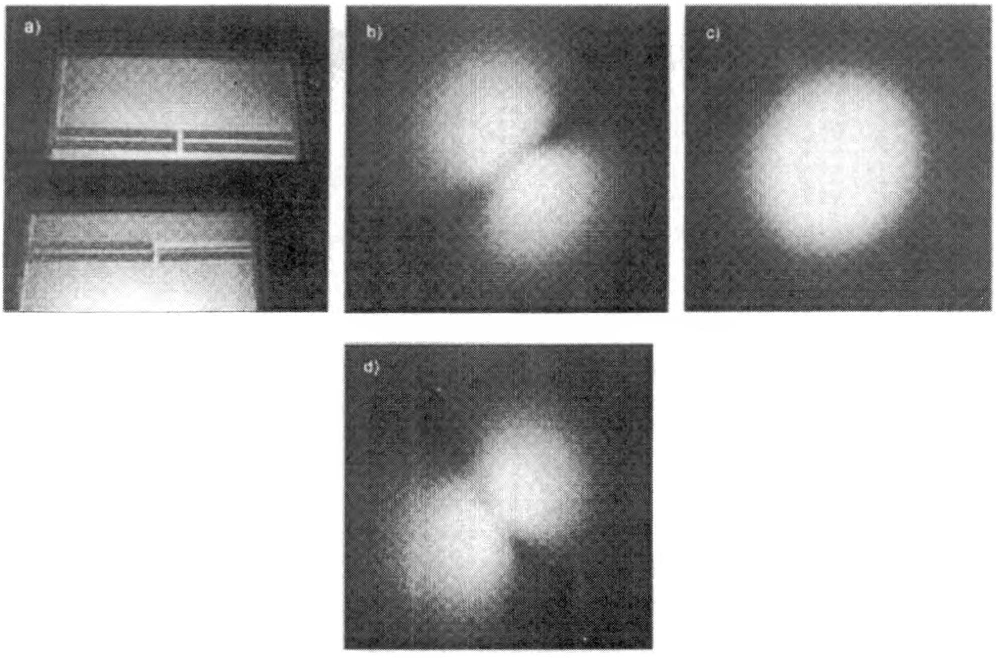

Fig. 4. Correct (**b** and **d**) two-mode and wrong (**c**) single-mode speckle patterns obtained by suitable positioning of D-type single-mode fiber with respect to the sensing fiber (shown in **a**) as right and left fibers, respectively.

2.3. Selection of fiber output speckle pattern for sensor applications

The type of RWD applied has resolution which prefers an application of a few-mode optical fibers. From technical point of view, all kinds of intensity distribution patterns shown in Fig. 1 could be used. However, speckle pattern changes for two-mode fiber are the most representative. This fiber offers a possibility of classifying the obtained speckle pattern changes with respect to external perturbation introduced.

A few-modes fiber always guides the fundamental mode, which can disturb output speckle pattern. For this reason, a special launching technique must be used for injection. In our system, we used a piece of a single-mode highly birefringent (HiBi) optical fiber as the input fiber to a two-mode sensing fiber. The launching condition has been obtained by suitable positioning of those fiber ends with micrometer resolution (Fig. 4).

3. Experimental results

The scheme of the experimental set-up of the two-mode fiber-optic external perturbation sensor is shown in Fig. 5. The coherent linearly polarized beam from a He-Ne laser pigtailed with the D-type HiBi fiber, suitably illuminates, through a special splice, the single-mode optical fiber for wavelength of 780 nm. The output speckle pattern has been magnified to 2 mm diameter by a microscope objective (MO). The RWD placed in the Fourier plane can detect spatial frequency about 40 c/mm and 32nd ring by suitably chosen focal length of lens equal to 600 mm. In the version of RWD that was applied, there were 32 wedge- and 32 ring-shaped detector elements in each half of silicon sensor of one-inch diameter. The existing software gives the possibility for simultaneous registration of up to twenty words, each of them containing up to twenty different distributions. The data taken in this way is used as a base for the neural network (NN).

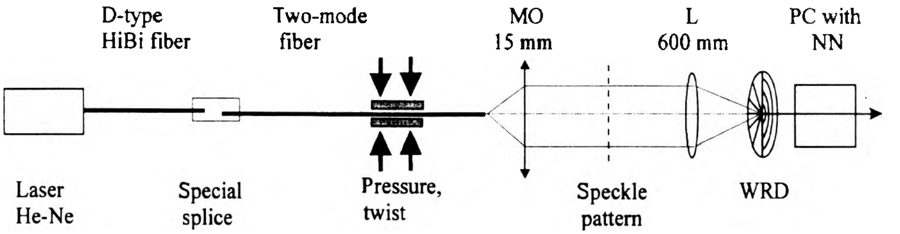

Fig. 5. Scheme of two-mode fiber-optic sensor.

The external perturbations such as: static pressure, electric field, pure bending, twist or magnetic field change the intermodal interference conditions. Then they change output speckle pattern as described in relation (1). In the experiment, the static pressure and pure twist have been used, because in our two-mode optical fiber sensor, these perturbations can generate two main types of a change in speckle

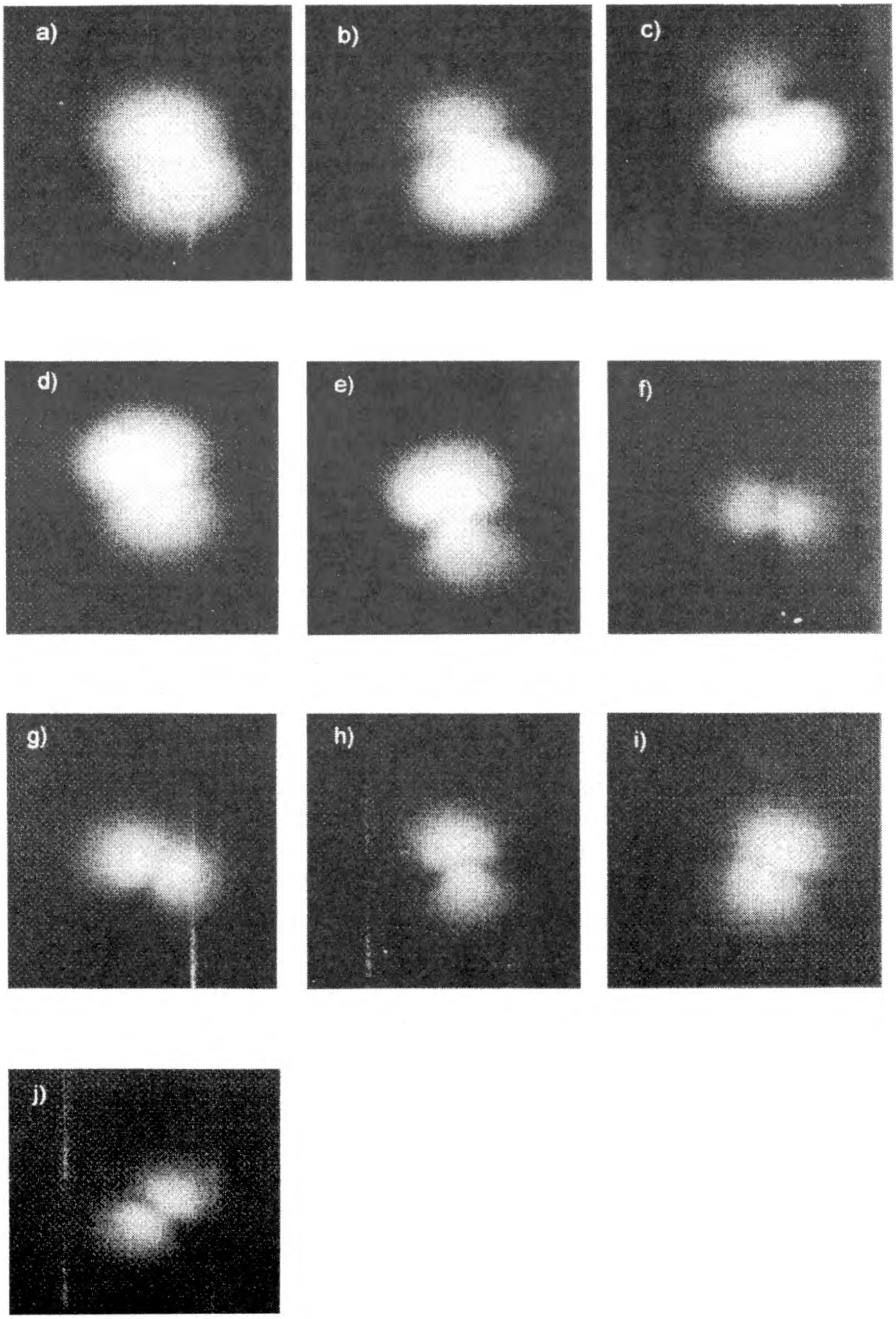

Fig. 6. Changes of the speckle pattern connected with the effect of the external perturbation on sensing part of two-mode optical fiber: **a**–**e** – the effects of pure pressure, **f**–**j** – the effects of pure fiber twist.

pattern [9]. The first one is power "transfer" between modes without changes of the polar angle of speckle pattern (Fig. 6**a**–**e**). Those changes can be combined with such perturbations as a symmetrical pressure (or electric field). The second one, connected with fiber twist (or axial magnetic field), is a rotation of speckle pattern without changes of power "distribution" (Fig. 6**f**–**j**).

The changes observed in radial (r) and polar (θ) image coordinates are exactly transformed by the FT. As the orientation of the input spatial frequencies varies, the angle θ of the FT distribution also rotates. As the scale of input object changes, the radial distance, at which the frequency peaks are located, also scales. Thus, spatial frequency and orientation information is conveniently available in the FT plane representation due to appropriate sampling by RWD. The results of this sampling are shown in Fig. 7. The analysis of this set of images has shown that for pressure

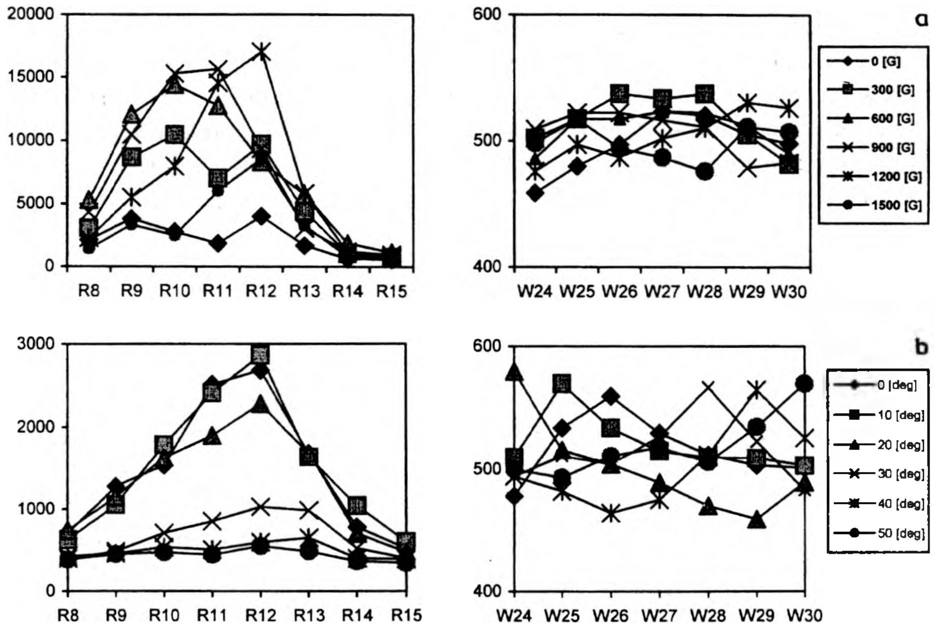

Fig. 7. Changes of diffraction pattern intensity in selected RWD elements (ring R8–R15, wedge W24–W30), for pressure (**a**) and twist (**b**).

(Fig. 7**a**) the main changes are observed in spatial frequencies without changing their angular position, whereas for twist (Fig. 7**b**) the main changes are observed in the angular position without changing spatial frequencies.

The software NN has been used for identification of the above pattern. In this experiment, a cumulative back-propagation mode is used. The input layer has 32 input neurons. It was ring-only or wedge-only logarithmic data value for pure twist or pressure, respectively. The hidden layer used 20 neurons, whereas the output layer used only one neuron. The results of recognition of six images tested (T0–T5), each

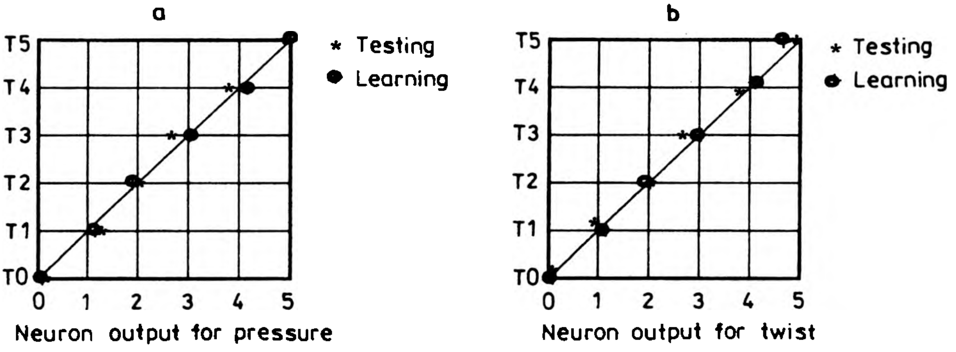

Fig. 8. Result of recognition of T0–T5 images. Output neuron 0–5 for: a – pressure from 0 to 1500 G at 300 G intervals, respectively; b – fiber twist from 0 deg to 50 deg at 10 deg intervals, respectively.

of them containing five independent measurements, are shown in Fig. 8. The output neuron of NN has been connected with a suitable value of pressure or twist applied in the experiment. As one can see from Fig. 8, the kind of disturbance (the pressure or the twist) has been identified by the NN with good accuracy after 500 learning cycles. For the computer system applied, the learning time is about 300 s, and our calculation gives measurement error about 2%. This is a good agreement between the test and learning processes.

4. Summary and conclusions

The possibility of applying the Fourier transform to fiber-optic sensor has been shown. This system can be characterized by sensitivity changing in a wide range from the value characteristic of interferometric fiber-optic sensor to the value characteristic of polarimetric one. The sensitivity of such a system is mainly dependent on a number of modes guided in an optical fiber. The two-mode fiber used in our work has sensitivity similar to that of the two-beam interferometer, with the advantage being a better environmental stability. The main problem concerning this sensor is that changes of interaction placed along the fiber can generate changes in output speckle pattern. A bigger number of guided modes average an intermodal interaction, and causes that output speckle pattern is less sensitive to change of interaction position along the fiber. However, speckle pattern changes decrease with an increasing number of guided modes, and for multimode interaction, the RWD cannot distinguish between them. Then, this value should be optimized for any sensor application. This problem is dealt with by the authors for fiber-optic static pressure sensor to be applied for the monitoring of highway load.

The method for identification of the perturbations generated in fiber-optic sensor applied in the present paper has two main advantages. First, progress in computer developing gives a possibility of using effective hardware or software neural networks. The problem of perturbation identification, difficult from an analytical point of view, can be solved by a simple neural network learning process. Moreover, in this process the effect of environment disturbances can be eliminated by suitable network learning. Second, hardware system of the RWD can be replaced by a computer-generated hologram for diffraction-pattern sampling. Hence, the sensor system can be more economical and more compact. Such an approach creates also a possibility of maximizing the system accuracy by a suitable choice of a number of generated ring-wedge elements.

Acknowledgements — The authors would like to express their thanks to Ryszard Świłło, Ph.D., for his helpful advice, and Dr. Jan Wójcik for supplying the special two-mode and HiBi elliptical core optical fibers. This work has been done under financial support of the State Committee for Scientific Research (KBN), Grant No. 8T11C 036 12 and the MUT Statutory Activity (PBW), No. 822, in 1998.

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Received November 16, 1998
in revised form February 8, 1999