



Adaptive neuro-fuzzy prediction of modulation transfer function of optical lens system



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HIGHLIGHTS

- The quantitative assessment of image quality by modulation transfer function (MTF).
- Graphical description of the sharpness and contrast of an imaging system.
- Adaptive neuro-fuzzy system to estimate MTF value of optical system.
- Adaptive neuro fuzzy application.

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ABSTRACT

The quantitative assessment of image quality is an important consideration in any type of imaging system. The modulation transfer function (MTF) is a graphical description of the sharpness and contrast of an imaging system or of its individual components. The MTF is also known and spatial frequency response. The MTF curve has different meanings according to the corresponding frequency. The MTF of an optical system specifies the contrast transmitted by the system as a function of image size, and is determined by the inherent optical properties of the system. In this study, the adaptive neuro-fuzzy (ANFIS) estimator is designed and adapted to predict MTF value of the actual optical system. Neural network in ANFIS adjusts parameters of membership function in the fuzzy logic of the fuzzy inference system. The back propagation learning algorithm is used for training this network. This intelligent estimator is implemented using MATLAB/Simulink and the performances are investigated. The simulation results presented in this paper show the effectiveness of the developed method.

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1. Introduction

The characteristic quality of an optical system is usually considered by a function of its ability to discern the smallest object from the farthest distance. The modular transfer function (MTF) is a measure of system response in terms of spatial frequency and is probably the best measure of performance for such systems [1,2]. MTF data can be used to determine the feasibility of overall system expectations [3].

The MTF, a quantitative measure of image quality, is far superior to any classic resolution criteria [4]. MTF of an optical system is a measure of its ability to transfer contrast at a particular

resolution level from the object to the image. In other words, MTF is a way to incorporate resolution and contrast into a single specification. From a visual standpoint, high values of MTF correspond to good visibility, and low values to poor visibility. But this quality of visibility depends on frequency. Perhaps an easy way to interpret MTF is by thinking of imaging a target with black and white lines, i.e. a target with 100% contrast. It is a known fact that no optical system at any resolution can fully transfer this contrast to the image due to the diffraction limit. In fact, as the line spacing on the target is decreased, i.e., the frequency increases, it becomes increasingly difficult for the optical system to efficiently transfer this contrast. Therefore, as the frequency increases, contrast of the image decreases and an MTF graph, which relates the fraction of transferred contrast as a function of the line frequency, is the best way to observe such performance degradation [5–7].

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However, while the MTF is such an important resource to objective evaluation of the image-forming capability of optical systems, it is usually obtained experimentally, thus, leaving researchers without an analytical (mathematical) solution in terms of measuring the performance [8,9]. Although there are many analytical MTF expressions proposed for optical systems, they usually do not completely fit experimentally obtained data [10–12]. Accuracy of commercial MTF measurement systems ranges from 5% to 10% in absolute MTF, however obtaining accuracy to within 1% is also possible. Thus, existence of an analytical expression that better fits the experimentally obtained MTF, would help researcher to achieve better determination of the image quality of the optical system at the design phase [13–15]. This is rather important as analytical expressions are employed at the modeling stage of systems and modeling is a powerful tool to gain insight into the expected performance of systems at the beginning without having to build the whole system. Hence, a less accurate mathematical model will produce reduced expectations in terms of system performance [16–18].

The MTFs are non-linear functions that need accurate identification for the best determining of an image quality [19]. Aiming at optimizing such systems to ensure optimal functioning of the unit, new techniques are used today such as the fuzzy logic (FL), artificial neural network (ANN) and neuro-fuzzy.

Artificial neural networks are flexible modeling tools with capabilities of learning the mathematical mapping between input and output variables of nonlinear systems. One of the most powerful types of neural network system is adaptive neuro-fuzzy inference system ANFIS [20]. ANFIS shows very good learning and prediction capabilities, which makes it an efficient tool to deal with encountered uncertainties in any system. ANFIS, as a hybrid intelligent system that enhances the ability to automatically learn and adapt, was used by researchers in various engineering systems [21–27]. So far, there are many studies of the application of ANFIS for estimation and real-time identification of many different systems [28–36].

However, there are no papers dealing with the determination of the MTF of an optical system by using of adaptive neuro-fuzzy systems. The key goal of this investigation is to establish an ANFIS for estimation and simulation of the MTF of the actual optical system without having the analytical model of the system itself. An attempt is made to retrieve correlation between spatial frequencies (tangential and sagittal) and input field angles in regard to MTF. That system should be able to forecast the MTF in regards to the main MTF parameters. The ZEMAX software was chosen to design the analyzed optical layout and to extract training experimental data for the ANFIS modeling. The basic idea behind the soft computing methodology is to collect input/output data pairs and to learn the proposed network from these data. The ANFIS is one of the methods to organize the fuzzy inference system with given input/output data pairs [37,38]. This technique gives fuzzy logic the capability to adapt the membership function parameters that best allow the associated fuzzy inference system to track the given input/output data [39].

2. Modulation transfer function

The MTF, describing the resolution and performance of an optical system, is the ratio of relative image contrast divided by relative object contrast. When an object is observed through an optical system, the resulting image will be fairly degraded due to inevitable aberrations and diffraction phenomena. Aberration is the loss of image in an optical system when the system fails to focus the incoming beams properly. Diffraction is another type of image expiration caused by reflections and deviations of the light

beams at transition points. While it is possible to rule out aberration by means of using appropriate optical techniques, due to the natural structure of light, even with the optical systems designed in the best way possible, it is not possible to totally eliminate the effect of diffraction. Hence, it is said that all optical systems are diffraction limited. Moreover, real optical systems will not fully adjust to the design data. Manufacturing errors, assembly and alignment errors in the optics will drop the overall imaging performance of the system. As a result, in the image, bright highlights will not appear as bright as they do in the object, and dark or shadowed areas will not be as black as those observed in the original patterns. In general a target can be defined by its spatial frequency (number of bright and dark areas per millimeter) and the contrast (the apparent difference in brightness between bright and dark areas of the image). Performance measurement of any diffraction-limited system is carried out by sensing a test object (usually a square, triple bar pattern) through the optical/electro-optical system. Effects of diffraction on contrast with respect to the increasing frequency are given in Fig. 1.

In an electrical system, general information about a circuit can be obtained from its frequency response (i.e., transfer function). Similarly, in an electro-optical system, general information about the system could also be extracted from its spatial frequency response. If the distance between consecutive target peak values is N (in millimeters), then the spatial frequency of the target is given by

$$R = \frac{1}{N} \quad (1)$$

This term has units of line pairs per millimeter (lp/mm) in resolving cards. In afocal systems, generally, it is more common to use units of cycles/mrad. An afocal system is one in which the object or image is at infinity. Definition of the modulation in optical systems is as follows:

$$\text{Modulation} = \frac{B_{\max} - B_{\min}}{B_{\max} + B_{\min}} \quad (2)$$

where $B_{\min}$ and $B_{\max}$ denote values of minimum and maximum amplitude, respectively, as illustrated in Fig. 2. By convention, the modulation transfer function is normalized to unity at zero spatial frequency. For low spatial frequencies, the modulation transfer function is close to 1 (i.e. 100%) and generally descends as the spatial frequency increases until it reaches zero. The contrast values are lower for higher spatial frequencies as shown in Fig. 1. When the contrast value reaches zero, the image becomes a uniform shade of grey. The intersection of the modulation function and the minimum acceptable modulation gives the “resolution power limit” as shown in Fig. 3. The minimum acceptable modulation level is also known as detection threshold or noise equivalent modulation level. In some cases resolution limit, on its own, is not adequate to determine the performance of a system. In Fig. 3, systems A and B have the same resolution power, but system A will produce a better image because the contrast of A at the lower frequencies is better.

3. Optical lens system

As optical system for analyzing and extracting experimental training ANFIS data, doublet lens system was chosen. Table 1 shows general data of the lens system.

Fig. 4 shows the doublet lens system with 11 input fields. The input fields are used for experimental data extraction i.e. MTF data for the ANFIS training. Every single field has different input angle from 0 up to 10 degrees respectively. The field's ranges are used as initial ANFIS training data. Afterwards the trained ANFIS model could be easily updated with new data. In order to simplify the

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