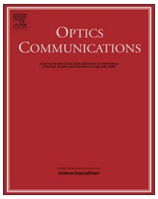
Optics Communications 399 (2017) 87–97

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom



Imaging quality evaluation method of pixel coupled electro-optical imaging system

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ARTICLE INFO

OCIS codes:
060.2350
060.2270
110.4850
120.4800

Keywords:
Fiber-optic image bundles
Evaluation of imaging quality
Modulation transfer function
Pixel coupling error
Oscillation convergence

ABSTRACT

With advancements in high-resolution imaging optical fiber bundle fabrication technology, traditional photoelectric imaging system have become “flexible” with greatly reduced volume and weight. However, traditional image quality evaluation models are limited by the coupling discrete sampling effect of fiber-optic image bundles and charge-coupled device (CCD) pixels. This limitation substantially complicates the design, optimization, assembly, and evaluation image quality of the coupled discrete sampling imaging system. Based on the transfer process of grayscale cosine distribution optical signal in the fiber-optic image bundle and CCD, a mathematical model of coupled modulation transfer function (coupled-MTF) is established. This model can be used as a basis for following studies on the convergence and periodically oscillating characteristics of the function. We also propose the concept of the average coupled-MTF, which is consistent with the definition of traditional MTF. Based on this concept, the relationships among core distance, core layer radius, and average coupled-MTF are investigated.

Results show that the coupled-MTF oscillation converges to a fixed value when the deviation between a spatial frequency of input signal and Nyquist frequency is 1% and when the total number of pixels in the coupled system is more than 1000. The minimal frequency deviation corresponds to the slow velocity of the oscillational convergent. The oscillation amplitude of coupled-MTF differs in tangential and sagittal directions in a manner related to the corresponding pixel coupling error. The coupled-MTF periodically oscillates with the alignment error between the coupled pixel. One cycle is equivalent to the diameter of fiber cladding. The observation from the simulations further reveal that the distance between adjacent fiber cores and the dimension of core layer are directly related to the system imaging quality and the signal-to-noise ratio. Moreover, the average coupled-MTF can be used to quantitatively describe the function of related parameters and the imaging quality of the system.

1. Introduction

Numerous single fibers can be arranged in accordance with a certain rule and form a fiber-optic image bundle to transmit image information, such as fiber-optic image bundles that have good arrangement quality, 1024×768 resolution, Φ 6 µm cladding diameter, and visible to near-infrared spectral range [1]. Comprehensive performance can be improved by adding fiber-optic image bundles to a traditional imaging system. For example, adding fiber-optic image bundles to a Raman imaging system can improve signal-to-noise ratio (SNR) [2]. The scale of an optical system can be greatly reduced by using fiber-optic image bundles coupled with array detector in a high-performance ultra-wide-angled lens [3]. Combining fiber-optic image bundles in a hyperspectral imager can also considerably enhance the side width of slices [4].

However, a two-level coupled discrete sampling system becomes involved when fiber-optic image bundles are added to an optical imaging system with an array CCD. This limits the application of the traditional mathematical methods for MTF. First, the coupling error of the pixels leads to the difficulty of mathematic derivation based on Fourier transform. Second, for multistage discrete sampling systems, the transmittance of intensity at different coordinates of the array is different because of the coupling error of the pixels. Therefore, the applicability of the MTF cascade multiplication and spatial invariant assumption is no longer valid. These theoretical difficulties of traditional imaging quality evaluation models entail substantial research work. For instance, Donald et al. [5] experimentally investigated the influence of fiber-optic image bundles on the imaging quality of optoelectronic circuits. Seki et al. [6] reported the relationship of single fiber radius in the bundles with the imaging quality of a photoacoustic

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http://dx.doi.org/10.1016/j.optcom.2017.04.029
Received 10 November 2016; Received in revised form 10 April 2017; Accepted 11 April 2017
0030-4018/

imager. Ford et al. [7] discussed the issue of system imaging quality evaluation after fiber-optic image bundles are added to the swept-source optical coherence tomography (OCT) from the angle of the SNR and resolution. MTF can indicate the characteristics of imaging system responses to different spatial frequency domains. For example, oblique-edge scanning method is used to evaluate the coupled sampling system with fiber-optic image bundles and CCD [8], or a cascade multiplication method is still applied to calculate the MTF of a two-stage coupled discrete sampling system [9]. Other studies have been based on the output light intensity distribution of grayscale cosine distribution signal from the coupled discrete sampling systems and have discussed the model of MTF according to its definitions [10–13]. This concept aims to prevent discrete coupling characteristics from interfering with transfer function calculation. The coupling contrast transfer function (CTF) between line-array fiber-optic image bundles and linear CCD is derived on the basis of the definition of CTF [14]. Related experiments have also revealed new features different from traditional CTF. To extend its application in hyperspectral remote sensing fields, we extensively investigated the coupled-MTF of pixels between an array of fiber-optic image bundles and CCD. A mathematical model of the coupled-MTF of a two-stage discrete sampling system and an initial-position average coupled-MTF was established. Some new characteristics of the function were also analyzed. Our study provided a theoretical basis for the optical design of fiber-optic imaging system and subsequent experimental verification.

2. Model and calculation

The main model of photoelectric imaging system using an array fiber-optical image bundle is shown in Fig. 1. This model includes an optical telescope, array fiber-optical image bundles, a coupling objective lens, and CCD array.

The principle sketch involves the front-telescope system, which obtains the object image (λ1–λ2) to the focal plane at a certain magnification. Fiber-optic image bundles do not change their numerical aperture (N.A.), and the optical fiber core diameter is considerably greater than the radius of an Airy-disk radius of a telescope system. The coupling lens is used to couple with an optical fiber beam output image to CCD. The input window of the fiber-optic image bundle is arranged on the focal plane of the telescope lens. Moreover, the output window of the bundle is positioned on the object surface of the coupling objective lens. The CCD-sensitive surface is located on the imagine focal plane of the coupling objective lens.

The ideal situation is shown in Fig. 2(a). The diameter of a single fiber of a bundle is the same as the pixel size of CCD, hence allowing for one-to-one coupling. The imaging quality of the whole imaging system agrees with the theoretical design. However, the actual alignment of the imaging system introduces pixel alignment error. A coupling error exists between the pixels of the fiber bundle and the CCD (Fig. 2(b)). Consequently, the imaging quality of the system changes compared with the theoretical situation.

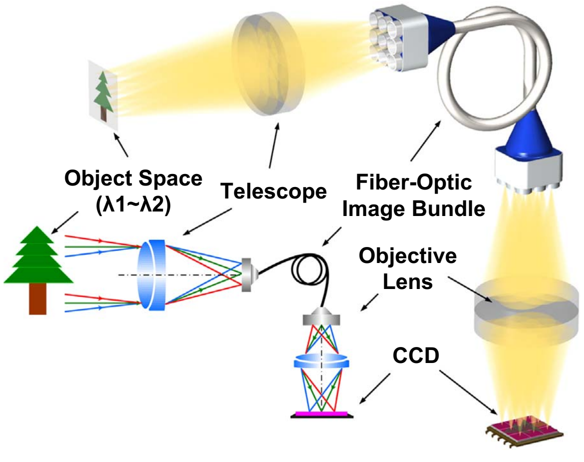

Fig. 1. Principle of the array fiber-optic image bundles.

The R in Fig. 2 represents the radius of the fiber cladding, whereas r represents the radius of the fiber core. Δi and Δj represent the pixel coupling deviations in the tangential and sagittal directions, respectively, δ denotes the initial positional deviation between the grayscale cosine distribution target and the pixel coupling array. We define the "coupled modulation transfer function" (coupled-MTF) of the system according to the output response of the system to the input signal of the grayscale cosine distribution to avoid the limitation of the spatial invariant assumption. The physical model is shown in Fig. 3.

The optical target of the grayscale cosine distribution enters the telescope imaging system after a two-time discrete sampling of the fiber-optic image bundle and the CCD. Finally, the target image is obtained in accordance with the grayscale level and its distribution of each pixel. The modulation depth of the output image can be calculated by using the concept of statistical averages. Then, we develop the coupled-MTF mathematical model of the coupled discrete sampling system through the intensity modulation definition. In addition, the cosine signal is oriented in two directions orthogonal to each other in the coupled-MTF model system. As such, the MTF model of the coupled discrete sampling system in the tangential and sagittal directions is established.

We should explain the simplified section before the detailed derivation of the coupled-MTF expression. (1) The actual coupling deviation exists in three-dimensional space. The coupling error with six free dimensions between the coupled systems is existent. However, the defocusing errors and tilt errors in three-dimension can be controlled to sub-micron and sub-second order by the traditional method. The accuracy of this magnitude can be ignored for the output image quality for 1000×1000 coupled pixels. (2) The telescope and coupling objectives are traditional optical system. Hence, the MTF (f) in each field of view is the fixed value. (3) The long-distance transmission of the laser through the fiber introduces strong Gaussian characteristics of output signal. However, the fiber-optic image bundles mentioned in the paper is only used for the image transmission of wide spectral (350–750 nm). Moreover, the input beam itself does not have Gaussian characteristics. Therefore, the Gaussian characteristics of the output beam caused by the optical fiber transmission can be neglected [15]. Therefore we assume that each individual fiber in the bundles only integrally transmits the intensity distribution of the input beam rather than changing it within a single fiber. (4) The reference indicates that a large crosstalk in the fiber bundle is present when used to transmit laser beam. The crosstalk rate is generally −60 dB to −10 dB when the fiber bundle length is 100 m or more, whereas the fiber-optic image bundles mentioned in the paper are only used for wide spectral image transmission within a very short distance. In this case, the decrease of modulation caused by crosstalk is less than 1% [16,17], and the crosstalk rate is close to the fixed value. Therefore, in the following mathematical derivation, C is defined as the degree of modulation decrease caused by the average crosstalk rate in the fiber bundle.

First, the intensity cosine distribution target is used for the input signal. In this case, the signal distribution in the input window of the optical fiber is

$$I(x) = 1 + C_0(f)\cos(2\pi f(x + \delta)) \tag{1}$$

where, f, $C_0(f)$, and δ are the spatial frequency, modulation, and initial positional deviation of the input signal, respectively. With the Nyquist frequency $f_N = 1/(4R)$, the intensity of the output signal of any row i and column j pixel in the fiber array is given by