INTRODUCTION TO MODULATION TRANSFER FUNCTION

MODULATION TRANSFER FUNCTION (MTF)

The Modulation Transfer Function (MTF) curve is an information-dense metric that reflects how a lens reproduces contrast as spatial frequency (resolution) varies. MTF curves can be used to compare the performance of multiple lenses and can help determine if an application is actually feasible with the respective lens. They offer a composite view of how optical aberrations affect performance at a particular set of fundamental parameters dictated by the application's need. It is important to understand that changing almost any setting on a vision system, including the fundamental parameters, will change the performance characteristics of the curve.

Figure 1 shows a common type of MTF curve, which describes the contrast vs. frequency (resolution). Typically the curve is given for the image plane of the lens and provides a broad overview of a lens's performance at a specific working distance, f/#, sensor size, and wavelength range. The frequency (noted on the x-axis) is given in cycles per millimetre or line pairs per millimetre. A cycle or a line pair is a black and a white line next to each other. The number of line pairs per millimetre can be converted to the size of a line pair or the size of a line. It stands for the size of a structure that an imaging lens can or cannot resolve (100 line pairs per millimetre => line pair size is 10 μm => line (or structure) size is 5 μm). The contrast (noted on the y-axis) describes how well the black and white lines can be distinguished. 100% contrast means one line is black and one line is white, the contrast is very high. 0% contrast means both lines are the same grey and cannot be distinguished from one another. For imaging systems 15-20% contrast is typically the minimum contrast needed for acceptable image quality.

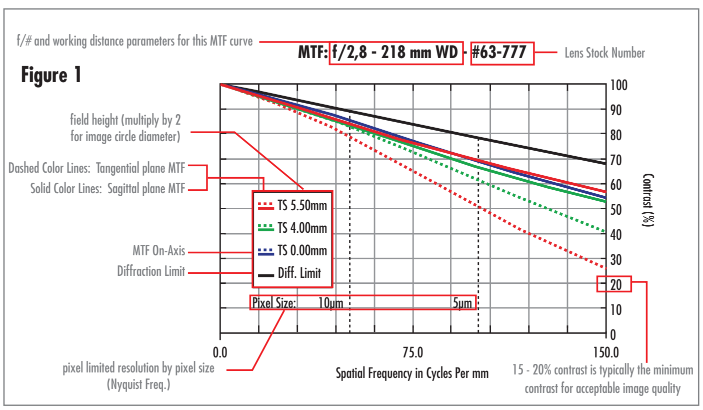

Figure 1: An MTF performance curve illustrates contrast vs. frequency

Multiple coloured curves (black, blue, green, and red) are displayed. The solid black line at the top is the diffraction limit of the lens, and represents the absolute upper limit of the lens performance. No matter how advanced the lens design becomes, it will never rise above this line. The additional coloured lines on the curve that are below the diffraction limit represent the MTF performance of the lens. They correspond to different field heights (positions across the sensor) that are to be used. In this case, there are three different field heights represented: on-axis (blue), which represents the centre of the image circle; 70% of the diameter of the image circle (green), which represents about half the image area; and the full image circle (red), which is the corner of the image sensor that is in use.

The other noteworthy feature within the curves is the difference between solid and dashed lines, represented on the curve by the letters T and S, which represent the tangential (T: yz) and sagittal, or "radial" (S: xz) planes of focus, respectively. These fields are different due to aberrations that are caused by asymmetry, such as astigmatism, which is why there is not a separate curve for tangential and sagittal on-axis. If element tilts or decentres existed, the asymmetry would cause there to be different T and S curves on-axis, as well.

In the following sections imaging lenses are compared to each other using MTF curves. In order to show what influence the different lens parameters have on the system performance, there is always one parameter that differs for each comparison: lens design, focal length, f/# or working distance.

Comparison of two different lens designs with the same focal length, 12 mm at f/2,8

Figure 2 shows two real life examples of MTF curves for two different 12 mm lens designs. The lenses have the same focal length, the same FOV, sensor, and f/#. They will produce systems that are the same size, but differ in performance. White light is used for the simulated light source.

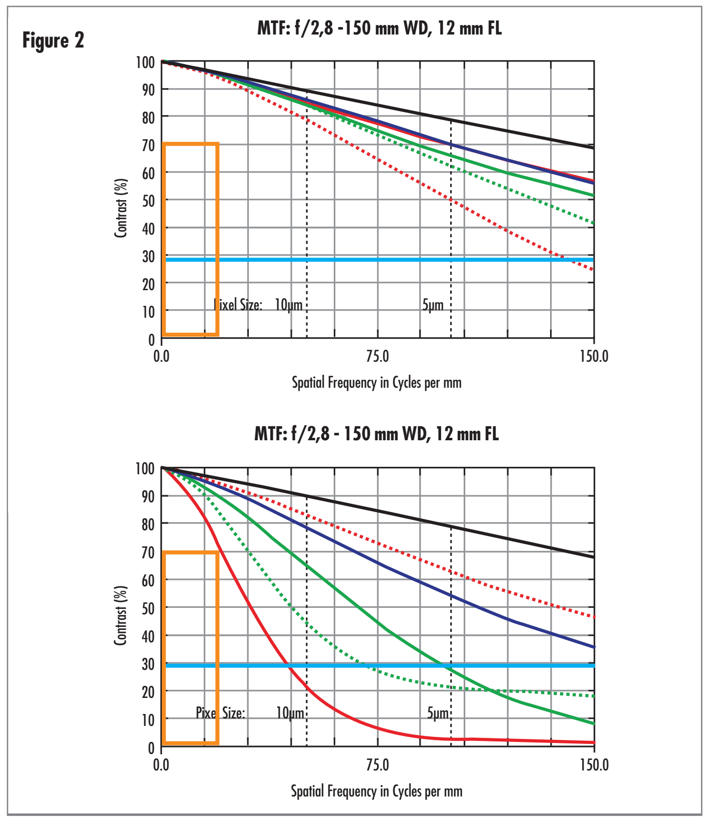

Figure 2: MTF Curves for Two Lens Designs a (top) and b (bottom) with the same focal length, f/#, and system parameters

In analysis, the horizontal light blue line at 30% contrast on Figure 2a demonstrates that at least 30% contrast is achievable essentially everywhere within the FOV, which will allow for the entire capability of the sensor to be well-utilized. For Figure 2b, nearly all of the field is below 30% contrast. This means that better image quality will only be achievable over a small portion of the sensor. Also to note, the orange box on both curves represents the intercept frequency of the lower performance lens in Figure 2b with 70% contrast. When that same box is placed on Figure 2a, tremendous performance difference can be seen even at lower frequencies between the two lenses.

The difference between these lenses is the cost associated with overcoming both design constraints and fabrication variations; Figure 2a is associated with a much more complex design and tighter manufacturing tolerances. Figure 2a will excel in both lower resolution and demanding resolution applications where relatively short working distances for larger field of view are required. Figure 2b will work best where more pixels are needed to enhance the fidelity of image processing algorithms and where lower cost is required. Both lenses have situations where they are the correct choice, depending on the application.

Comparison of two high resolution lenses with different focal lengths, 12 mm and 16 mm at f/2,8

Figure 3 shows the MTF curves of two different high resolution lens designs with different focal lengths (12 mm and 16 mm, both at f/2,8). The working distance is different in order to achieve the same field of view. The lens with the longer focal length shows a slightly better performance than the lens with the shorter focal length, although the difference is not as extreme as in the previous example. Again the blue line shows the minimum achievable contrast of the lens with the better performance and the orange box represents the intercept frequency of the lower performance lens.

Figure 3

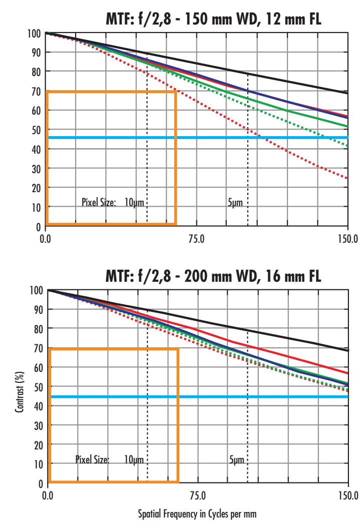

Figure 3: Two different high resolution lens designs a (top) and b (bottom) with different focal lengths at the same f/# and system parameters

Comparison of the same lens at different f/#s, f/4 and f/2

Figure 4 shows MTF curves of the same lens with different f/#s (f/4 and f/2). The working distance is the same as is the focal length. While the theoretical limit of Figure 4b is far higher, the performance is much lower. This is an example of how a higher f/# can reduce the aberrational effects, greatly increasing performance of a lens, even though the theoretical performance limit is greatly reduced. The primary trade-off besides resolution is less light throughput at the higher f/#. The yellow line shows the diffraction limited contrast at the Nyquist limit for the lens with f/4. The blue line denotes the lowest actual performance at the Nyquist limit at the same f/#.

Figure 4

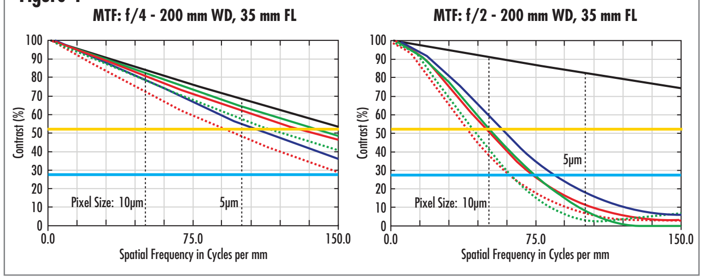

Figure 4: MTF curves for a 35 mm lens at the same WD and different f/#s: f/4 a (top) and f/2 b (bottom)

Comparison of a lens with 35 mm focal length at two working distances and the same f/#

For Figure 5, working distances of 200 mm (a) and 450 mm (b) are examined for the same 35 mm lens design at f/2. A large performance difference can be seen, which is directly related to the ability to balance aberrational content in lens design over a range of working distances. Changing working distance, even with refocusing, will lead to variations or reductions in performance as the lens moves away from its designed range. These effects are most profound at lower f/#s.

Figure 5

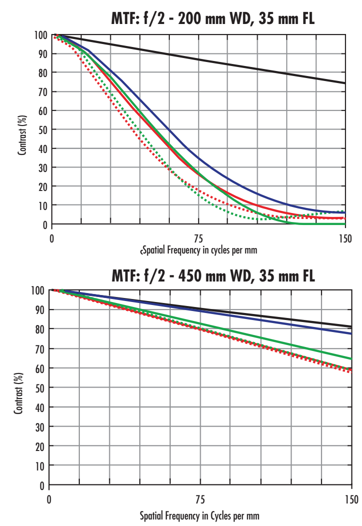

Figure 5: MTF curves for a 35 mm lens at the same WD and different f/#s: f/4 a (top) and f/2 b (bottom)

Conclusion

If one knows the basic principles of how to read an MTF curve, these curves are highly beneficial to quickly get an impression of the lens performance or compare different lenses before making the decision which imaging lens fits best to the given application. As shown in the comparison examples, different lens parameters can influence the performance of the imaging lens significantly and knowing which parameter changes lead to which performance changes can greatly help to improve the imaging system and produce images which can easily be analysed.

USA: +1-856-547-3488 | EUROPE: +44 (0) 1904 788600
ASIA: +65 6273 6644 | JAPAN: +81-3-3944-6210