DCTlab – DIDACTIC TOOL FOR THE STUDY OF IMAGE COMPRESSION

Sonja Grgić, Marta Mrak, Nikola Šprljan

University of Zagreb, Faculty of Electrical Engineering and Computing
Unska 3 / XII, HR-10000 Zagreb, Croatia

Abstract: *Current standards for the compression of still and moving images use Discrete Cosine Transform (DCT) which represents an image as a superposition of cosine functions with different discrete frequencies. Students and engineers specializing in image and video systems engineering need to understand why DCT is necessary and to understand the influence of DCT based image compression on picture quality. Therefore, education software "DCTlab" for the analysis of DCT application in image compression systems is developed. DCTlab is a library of MATLAB routines for DCT image compression with graphical user interface. DCTlab includes tools for spatial-frequency image analysis and procedures for image quality evaluation. The user can specify input image and compression parameters such as compression ratio or image quality. The compression results can be assessed and visual image quality of input and reconstructed image can be compared.*

Key words: *Image Compression,Discrete Cosine Transform, PSNR, PQS*

1. INTRODUCTION

The use of educational software is widely recommended as a complementary tool in image systems engineering education. The applications of imaging are numerous and include manufacturing, entertainment, remote sensing, publishing, interactive services, multimedia and the transfer of image data over communication lines. In many systems compression of image data should be used for efficient storage and transmission [1]. DCT is today's most widely used image compression technique [2]. Educational software DCTlab will help students to understand how DCT works in image compression system making sure that picture fits the system or conversely that system can handle the picture. Students can learn how to select compression parameters for specific application or image type and how to assess or measure picture quality to make sure that all the parts fit. Our goal is for our students to experience the active processing and manipulation of digital images.

2. THEORY

DCTlab is educational software with didactic objective and therefore it combines theory and practice in a very convenient way. The basic theory of DCT application in image compression is included in DCTlab as "Help" files which can be first presented to the user. The user has the possibility to familiarise himself with the theory associated with the subject. "Theory" is divided into few parts: Compression of Still Images, Discrete Cosine Transform, JPEG Compression and Picture Quality Assessment.

2.1. Compression of Still Images

A typical still image contains a large amount of spatial redundancy in plain areas where adjacent picture elements (pixels, pels) have almost the same values. It means that the pixel values are highly correlated. In addition, still image can contain subjective redundancy, which is determined by properties of human visual system (HVS). HVS presents some tolerance to distortion depending upon the image content and viewing conditions. The redundancy (both statistical and subjective) can be removed to achieve compression of the image data. In lossy compression scheme, image compression algorithm should achieve trade off between compression ratio and image quality.

2.2. Discrete Cosine Transform

Current standards for compression of still (e.g. JPEG [4]) and moving images (e.g. MPEG-1[5], MPEG-2[6]) uses DCT, which represents an image as a superposition of cosine functions with different discrete frequency [2]. The transformed signal is a function of two spatial dimensions and its components are called DCT coefficients or spatial frequencies. DCT coefficients measure the contribution of the cosine functions at different discrete frequencies. Most existing compression systems use square DCT blocks of regular size. Image is divided in blocks of M×N samples and each block is transformed independently to give M×N coefficients. The 2-D DCT and inverse DCT (IDCT) of an M×N block of pixel values (M=8, N=8 for JPEG) are defined as

$$F(u,v) = \frac{2}{\sqrt{N \cdot M}} \cdot \left[\sum_{x=0}^{M-1} \sum_{y=0}^{N-1} C(u) \cdot C(v) \cdot f(x,y) \cdot \cos \frac{(2 \cdot x + 1) \cdot u \cdot \pi}{2 \cdot M} \cdot \cos \frac{(2 \cdot y + 1) \cdot v \cdot \pi}{2 \cdot N} \right], \quad (1)$$

$$f(x,y) = \frac{2}{\sqrt{N \cdot M}} \cdot \left[\sum_{u=0}^{M-1} \sum_{v=0}^{N-1} C(u) \cdot C(v) \cdot F(u,v) \cdot \cos \frac{(2 \cdot x + 1) \cdot u \cdot \pi}{2 \cdot M} \cdot \cos \frac{(2 \cdot y + 1) \cdot v \cdot \pi}{2 \cdot N} \right], \quad (2)$$

where F(u,v) are transform coefficients, f(x,y) are pixel values and C(u) and C(v) are defined as

$$C(u), C(v) = \begin{cases} \frac{1}{\sqrt{2}}, \text{ for } u, v = 0 \\ 1 \ \ , \text{ for } u, v \neq 0 \end{cases} . \quad (3)$$

For many blocks within image most of the DCT coefficients will be near zero. DCT in itself does not give compression. To achieve the compression DCT coefficients should be quantized so that the near-zero coefficients are set to zero and remaining coefficients are represented with reduced precision that is determined by quantizer scale. The quantization results in loss of information, but also in compression. Increasing the quantizer scale leads to coarser quantization, which gives high compression and poor decoded image quality. The block-based segmentation of source image is fundamental limitation of the DCT-based compression system. The degradation is known as "blocking effect" and depends on block size and image content. Most existing systems use blocks of 8×8 or 16×16 pixels as compromise between coding efficiency and image quality.

2.3. JPEG baseline compression

JPEG compression starts by breaking the image into 8×8 pixel blocks. In grayscale image each pixel is a single byte, value between 0 and 255. Figure 1. illustrates the basic components of the JPEG compression for a grayscale image. After DCT in JPEG compression comes quantization which prepares the blocks for efficient entropy coding. Each DCT block of coefficients is divided by an 8×8 quantization matrix. Figure 2. shows example of quantization matrix proposed in JPEG.

The quantized coefficients are then linearized in a zigzag scanning order, Figure 3. The entropy coder (often called Huffman coder) assigns fewer bits to frequently used characters and more bits to seldom used characters. During decompression, the inverse DCT (IDCT) is taken to create an approximation of the original 8×8 block.

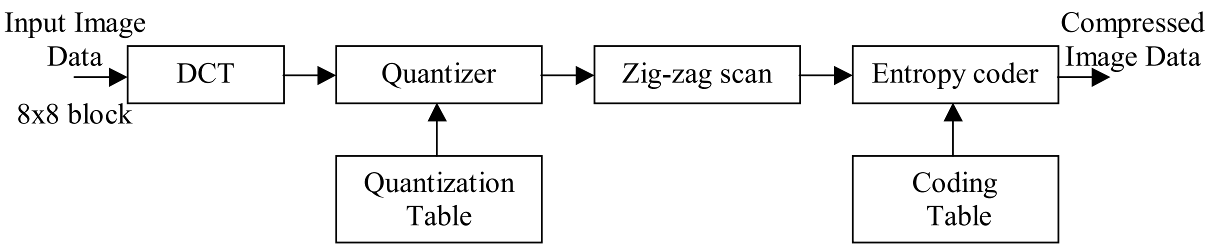


Figure 1. JPEG baseline compression

16	11	10	16	24	40	51	61
12	12	14	19	26	58	60	55
14	13	16	24	40	57	69	56
14	17	22	29	51	87	80	62
18	22	37	56	68	109	103	77
24	35	55	64	81	104	113	92
49	64	78	87	103	121	120	101
72	92	95	98	112	100	130	99

Figure 2. Quantization matrix

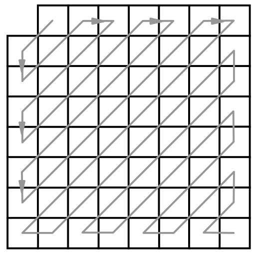


Figure 3. Zigzag scanning in JPEG

2.4. Picture Quality Assessment

The image quality can be evaluated objectively and subjectively [7]. Objective methods are based on computable distortion measures such as reconstruction error, Mean Square Error (MSE) and Peak Signal to Noise Ratio (PSNR). The reconstruction error is defined as the difference between input image x and reconstructed image x'. For N-pixel image MSE is defined as

$$MSE = \frac{1}{N} \cdot \sum_{i=0}^{N-1} \left(x_i - x'_i \right)^2 . \tag{4}$$

For the case of n bits per picture element of input image, PSNR can be defined as

$$PSNR = 10 \log \frac{(2^n - 1)^2}{MSE} \tag{5}$$

The traditional objective measures have long been recognised as inadequate because of their low correlation with human visual perception [8]. In fact, in image compression systems, the truly definitive measure of image quality is perceptual quality [9]. Therefore in addition to the commonly used PSNR, we chose to use a perception based subjective evaluation, quantified by Picture Quality Scale (PQS) [10]. PQS is a perception-based quantitative distortion measure. The PQS has been developed for evaluating the quality of compressed images. It combines various perceived distortions in image coders into a single quantitative measure and it correlates well with the subjective evaluation quantified by a mean opinion score (MOS) [11]. PQS method uses the five-grade impairment scale (5-imperceptible, 4-perceptible, but not annoying, 3-slightly annoying, 2-annoying, 1-very annoying) which is developed for subjective evaluation [12].

3. DCTlab – PROGRAM DESCRIPTION

As we have already mentioned, DCTlab is education software for the analysis of DCT application in image compression systems[13]. It is written in Matlab environment. Figure 4. shows typical DCTlab window with previously performed all steps from original to reconstructed image. Main program window is divided in parts, which represent steps in JPEG image compression, Figure 1. Supported images that can be loaded in program are Windows bitmap (.bmp) with linear greyscale colormap. Input image dimensions are restricted to be 256×256 or 512×512. Such limitations were necessary in order to simplify coding and just to focus on subject of study. For color images each component (luminance and chrominances) is treated separately and processed in similar fashion.

Original image is displayed in the left image frame and reconstructed image in the right frame. Any 8×8 pixel block can be selected in input image and its values can be examined in table next to it. Co-ordinates of the selected block are represented in form (x1, y1, x2, y2) in coordinate system where coordinates of the upper left corner of image are x,y=1,1 (x-horizontal axis,y-vertical axis). In next steps of program all tables show values for the block of pixels which position is defined by these coordinates. Input image is divided in the block of pixels and the size of block can be changed in the steps that are powers of 2 with range from 4×4 to whole image size (when image is treated like a single block). DCT is performed over each block independently and results can be examined in associated frame and table. DC shifting also can be applied to reduce the value of DC coefficient. Using DCT applied to the whole image, one-dimensional frequency analysis of DCT coefficients can be performed and spectral activity of input image can be evaluated. DCT coefficients as result of DCT show frequency contents of the image. The distribution of DCT coefficients depends on image contents. Images with high spectral activity (large number of high frequency DCT coefficients) are more difficult for compression system to handle. These images usually contain large number of small details and low spatial redundancy.

Reconstruction of original image is done by applying the inverse DCT, but for efficient compression entropy of data must be previously reduced. Threshold value for coefficients can be set in order to examine how reduced entropy affects reconstructed image quality (all coefficients with absolute value bellow the treshold are set to zero). After treshold setting, Compression Ratio (CR) can be computed as a ratio of number of all non-zero coefficients to number of all pixels in image. When size of block is 8×8 (as in JPEG), quantization and coding can be applied, leading to the real bit rate CR. The compression ratio can be adjusted by changing the quantization matrix, multiplying it with a selected constant. Zigzag pattern, quantization matrix and Huffman codes are user-definable (we performed experiments with JPEG recommended ones). For each compression ratio image quality can be evaluated objectively using PSNR or PQS or subjectively. The reconstructed image or reconstruction error can be presented to the user and user can assess visual picture quality. User can change compression parameters and compare the differences between quality measures.

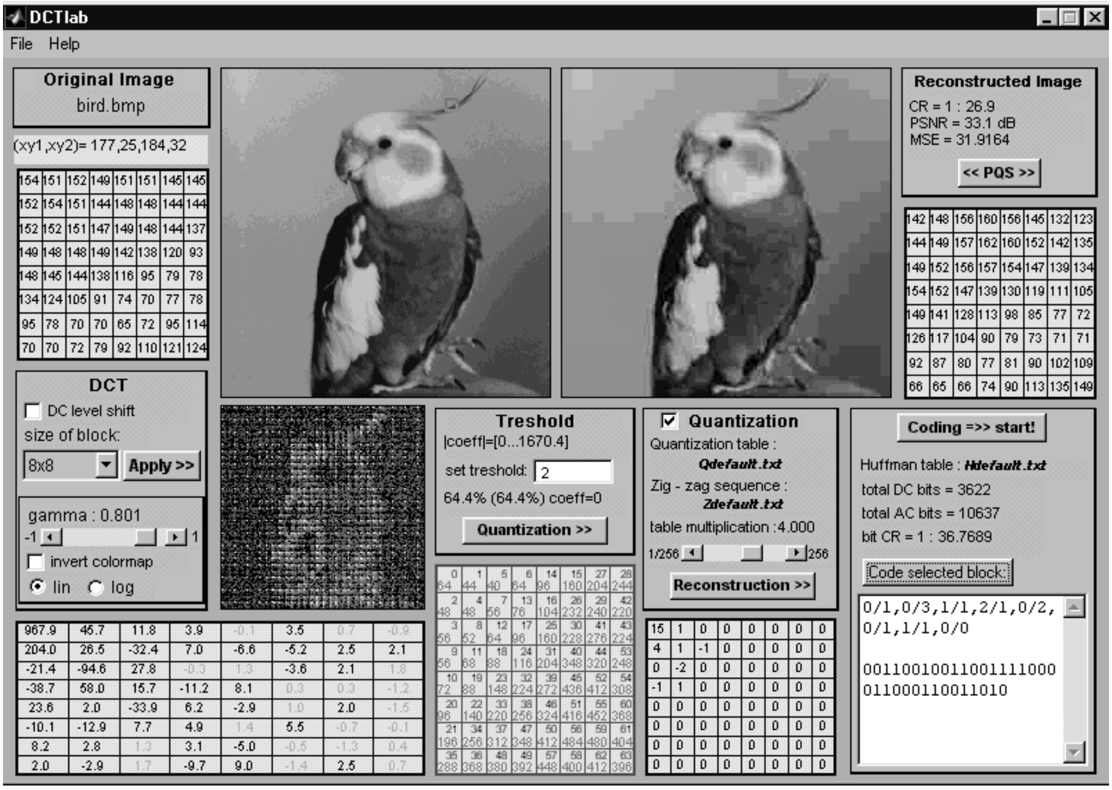


Figure 4. DCTlab window

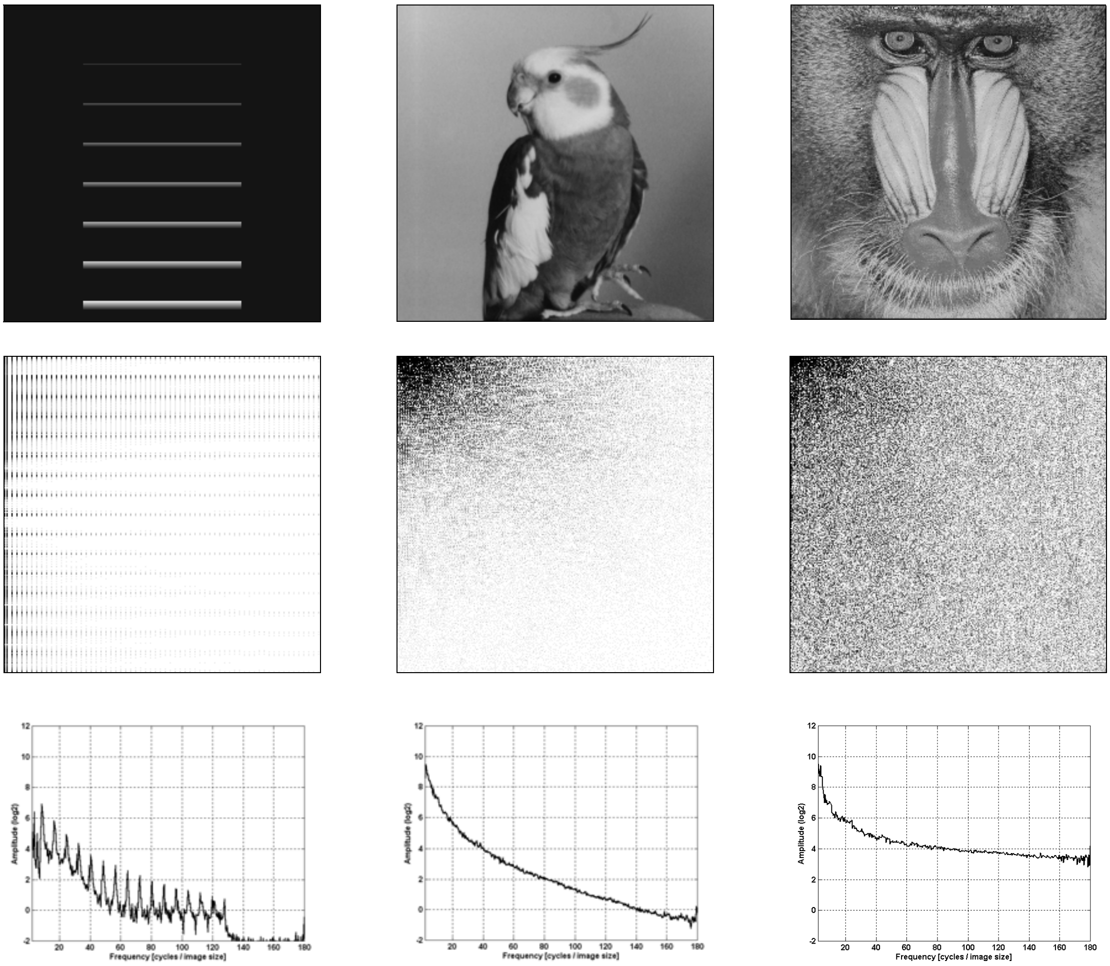
Using DCTlab user can learn a lot about frequency analysis of image, influence of image contents to compression results, correlation between image contents and picture quality and correlation between PSNR and visual image quality. The user can analyze the each step in DCT image compression algorithm and can see the effects of changes in compression algorithm to image quality. The user can learn how to obtain balance between compression ratio and image quality.

4. COMPRESSION RESULTS AND REMARKS

4.1. Frequency analysis

Calculations for frequency analysis are carried out with assumption that all coefficients with the same distance from the first DCT coefficient have the same absolute spatial frequency. Frequency analysis has been done for one geometric (a) and two photographic images ((b) and (c)) as shown in Figure 5. Figure 5. contains in the first and the second rows the distributions of image values before and after DCT and in the third row frequency analysis of input images (frequency is expressed as number of cycles per image size). Distributions of DCT coefficients contain black dots, which represent DCT coefficients. Moving across the top raw, horizontal spatial frequency increases. Moving down vertical spatial frequency increases.

Test image “Horizontal stripes” has large number of higher harmonics. Test image “Bird” has “continuous” spectrum as most photographic images have. Most of energy is concentrated at low frequency components so it can be efficiently compressed using DCT. Test image "Baboon" has large number of small details and therefore larger number of high frequency components.



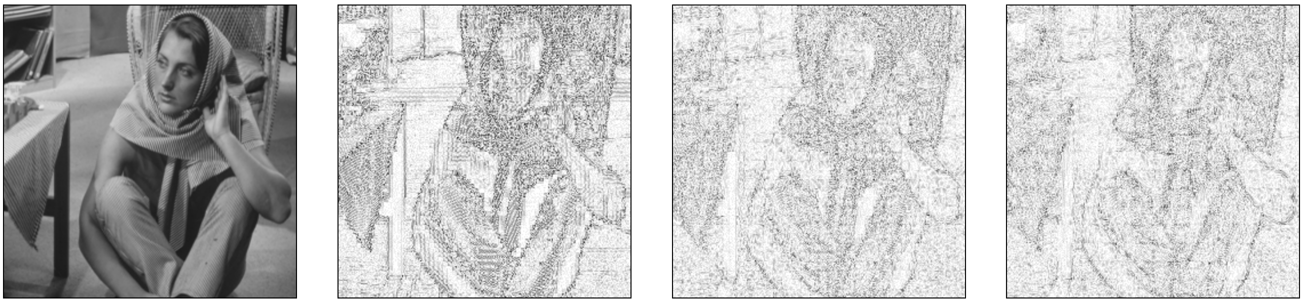
a) “Horizontal stripes” b) “Bird” c) "Baboon"

Figure 5. Frequency analysis of test images

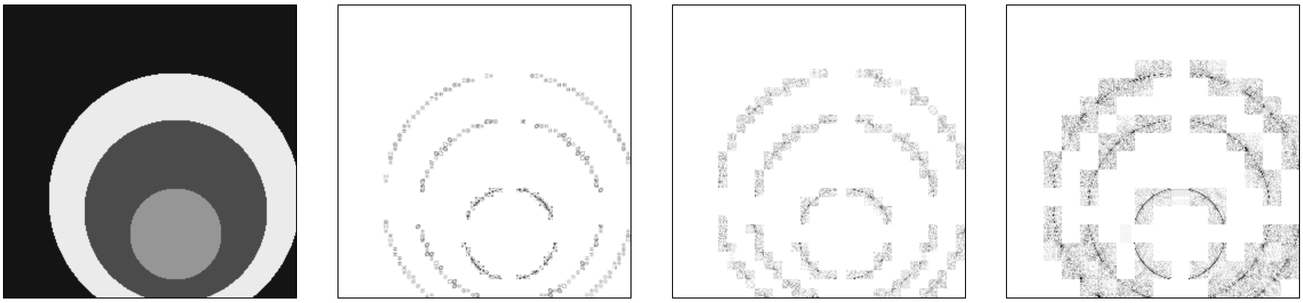
4.2. Comparison of Different Block Sizes

Figure 6. shows the comparison of reconstruction errors for image "Barbara" and image "Circles" (256×256, 8 bits/pixel) and four different block sizes for fixed compression ratio (CR=10:1). The comparison demonstrates reconstruction error images and their MSE values. The best result for image "Circles" is assigned for 4×4 blocks and for image "Barbara" for 16×16 blocks. It means that results depend on image contents. Consequence of relative high compression ratio is noise and blocking in the images.

Test image “Barbara” was used in next experiment. A total of 49 coded images were compared, representing a combination of seven different compression ratios and seven different block sizes. To compare efficiency of DCT for different block sizes, Figure 7. shows CR outputs versus MSE and PQS. We observe that 16×16 and 8×8 blocks work quite well for different compression ratios. At higher compression ratios 16×16 block sizes shows better results according to both MSE and PQS.



a)Test image "Barbara" | 4×4, MSE=68,30 | 8×8, MSE=33,70 | 16×16, MSE=30,56



b)Test image "Circles" | 4×4, MSE=3,05 | 8×8, MSE=4,15 | 16×16, MSE=16,15

Figure 6. Error images for different block sizes and test images a)"Barbara", b)"Circles"

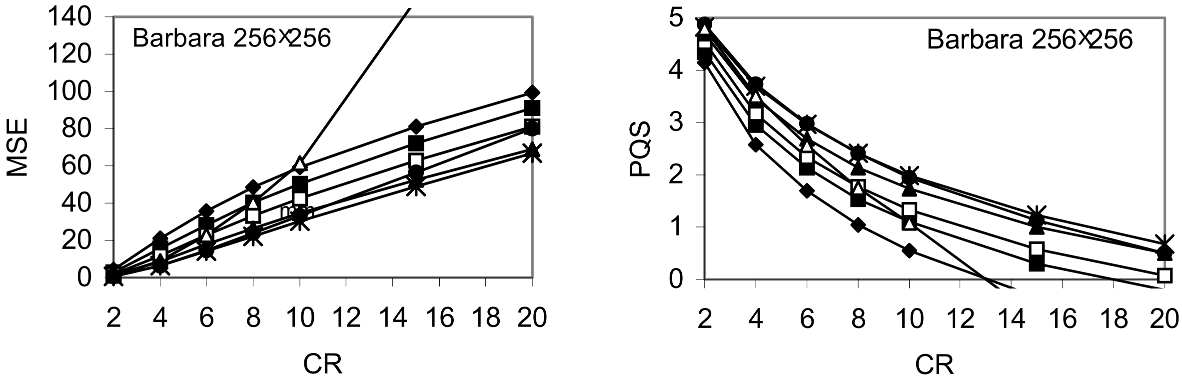


Figure 7. Results for image compression with different block sizes

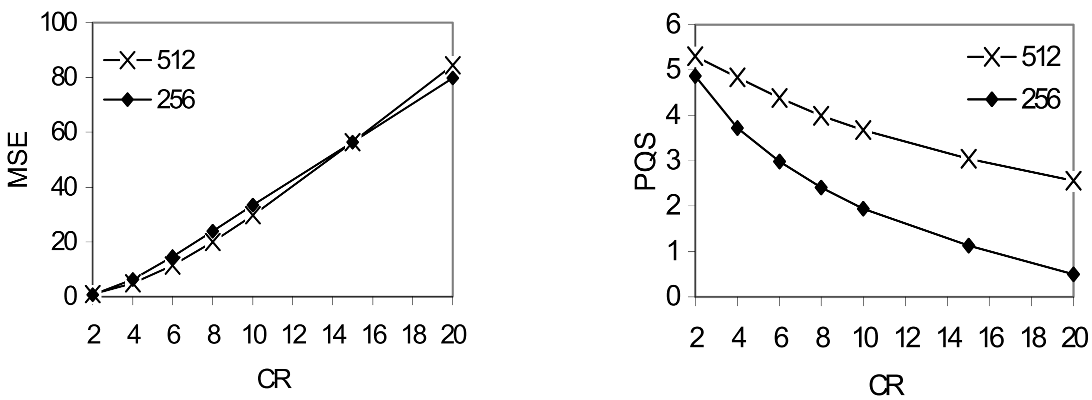


Figure 8. Comparison of MSE and PQS results for image“Barbara” (512×512 and 256×256)

4.3. Comparison of different image sizes

Figure 8. shows MSE and PQS results for two sizes of image "Barbara" (256×256 and 512×512). Images are compressed with different compression ratios which are achieved by changing the quantization scale. Both images are divided into blocks of 8×8 pixels. For both images similar results were observed for MSE, but for PQS there are large differences. 512×512 image has noticeable higher PQS values at all compression ratios. It means that input image resolution does not influence compression results if we consider only MSE. If we include PQS into consideration we can conclude that larger images will produce better visual image quality than smaller images at the same compression ratio.

5. CONCLUSION

Educational software DCTlab was implemented in the Matlab software packages to be used by electrical engineering students as a didactic tool for image compression. In this software it is possible to analyse the influence of each step in DCT compression algorithm to image quality. The user can select input image, size of block in DCT compression algorithm, quantization table and compression ratio. The user can select one block in input image and follow the changes of this block through all compression steps. The user can examine the compression results and can compare visual quality of input image and reconstructed image. DCTlab includes part for frequency analysis of input image and therefore students can explore the influence of image contents to image quality. Using DCTlab students become fully active participants in the learning process and achieve a much deeper, practical and more permanent understanding of the image processing concepts.

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