Mem. Fac. Agr. Kagoshima Univ., **34**, 109-122, 1998

Application of Soft X-ray Computed Tomography (I)

-Computer Simulation and Trial Production of Soft X-ray CT Scanner-

Yoshiaki HATTORI, Katsuya TERATOKO and Shinsuke FUJITA
(*Laboratory of Wood Technology*)
Received for Publication September 10, 1997

Introduction

The soft X-ray has longer wave length than the ordinary X-ray, having high absorption coefficient for a lot of substance. Because of this high absorption coefficient, the soft X-rays are suitable for testing thin and low density materials such as wood specimens. There are some studies which observed density distribution in woods by the soft X-ray[2,4,11]. However, there are quite few studies which applied the soft X-ray to Computerized Tomography (CT). The reasons for the scarcity in applications may be due to the following facts.

The first is that a limitation is fixed on the dimension of objects because of low energy of the soft X-ray. The second is that there is not any suitable detector for the soft X-ray applied to CT. The third is that there are not any suitable and convenient methods to avoid the artifact inevitably occasioned because of the beam hardening effect.

On the other hand, it is confirmed that the soft X-ray has an advantage in its controlling. For example, the apparatus is small and light in weight, and there is no need to pay attention for the hazard region. We should get more information from a low density contrast of the object with low X-ray absorption coefficient. Furthermore, it is not necessary to pay attentions to the scattered X-ray giving influence to CT images.

Nowadays, the X-ray CT scanners have not wider distribution except for medical services because of its large scaled frame setting and too high a price. And, the X-ray CT scanners for industrial use have a tendency to be of higher source voltage, because its targets has high X-ray absorption coefficients, such as steel, rock, ceramics and other inorganic substances.[6,7,9] If the objects were limited to those having low X-ray absorption coefficients such as wood and organic substances, with the dimension limited to a few centimeter in diameter, it would be possible to develop a compact typed CT scanner to be handled with low cost. Then, the scanner may be used in many industrial fields such as agriculture, forest product industries and so on.

In this paper, we are going to describe about technical knowledge obtained in developing a new soft X-ray CT scanner. A way how to correct an image artifact caused by the beam hardening effect was investigated. And, the density dependence of CT value obtained by the developed soft X-ray CT scanner was investigated, and the accuracy in the estimation of density was discussed.

Principles of X-ray CT and the artifact caused by beam hardening effect

Principles of X-ray CT scanner and their industrial application were described in many

This study was supported in part by a Grant-in-Aid for Scientific Research(c) (No.03660168) from the Ministry of Education, Science, Sports and Culture of Japan.

papers and books.[1,3,8,12] Some items relating to the development of the soft X-ray CT scanner were described in this section.

1. Principles of X-ray CT[1,3]

The principle in the case of monochromatic X-ray is as follows.

A cross section of an object is considered as a two-dimensional distribution of X-ray attenuation coefficients f (x,y). According to the parameters shown in Fig. 1, its projection (attenuated beam, d (s, θ)) has the following equation:

$$d(s,\theta) = \int_{Ls,\theta} f(x,y)\,dl \qquad (1)$$

The projection d(s, θ) is a line integral of attenuation coefficient f (x, y) along Ls, θ.

Attenuated beam is expressed as the following equation in case of the monochromatic X-ray.

$$I = I_0 \cdot \exp\{-d(s,\theta)\} \qquad (2)$$

The projection data d is calculated as the logarithm of the ratio of incident intensity (I_0) and absorbed intensity (I).

$$d(s,\theta) = \ln(I_0/I) \qquad (3)$$

The projections are obtained by some way, and from a set of these projections at many different angles, a cross sectional image is reconstructed by a back-projection.

In case of the polychromatic X-ray, since the linear attenuation coefficient is highly photon energy dependent, the spectrum of the X-rays is modified as they travel through the object body.

The energy spectrum of bremsstrahlung X-ray, that is continuous X-rays, is expressed as the following equation.

$$\psi(E) = 1.45 \cdot i_e \cdot Z \cdot (E_0 - E)(\mathrm{erg/cm^2/mA/keV}) \qquad (4)$$

Where i_e [mA] is a source current, E_0 [keV] is source voltage, and Z is atomic number (Tungsten Z=74). ψ(E) is intensity of X-ray with photon energy from E to E+dE.

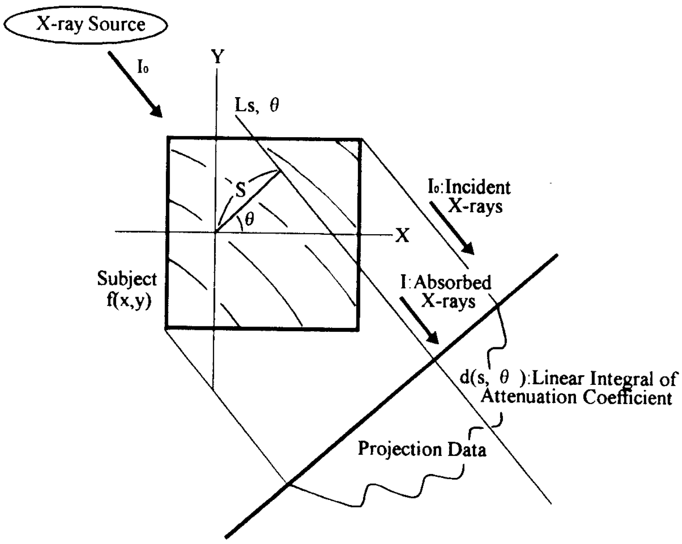

Fig. 1. Parameters describing X-rays projection as two-dimension.

Attenuation coefficient D is expressed as function of X-ray energy E. The attenuation coefficient is expressed as D(s, θ :E). The spectrum intensity of the attenuated X-ray is expressed as in the following equation.

$$\psi(E) = \psi_0(E)\cdot\exp\{-\int D(s, \theta : E)\, ds\} \qquad (5)$$

Where ψ_0 is an incident intensity spectrum. Intensity of spectrum of the continuous X-rays Ψ is obtained as an integral of the intensity spectrum as was expressed in the following equation.

$$\Psi = \int_0^{Em} \psi(E)dE = \int_0^{Em} [\psi_0(E)\exp\{-\int_{Ls,\theta} D(s, \theta : E)ds\}]\, dE \qquad (6)$$

Where $\int_{Ls,\theta}$ means a line integral along Ls, θ, and Em is the maximum source voltage.

The project data D is obtained with the following equation.

$$D = \ln(\Psi_0/\Psi) \qquad (7)$$

Where Ψ_0 is an incident X-ray intensity, and Ψ_0 is obtained with the following equation.

$$\Psi = \int_0^{Em} \psi_0(E)dE \qquad (8)$$

From a set of the projections obtained at a lot of different angles, a cross sectional image is reconstructed by a back-projection algorithm.

Some algorithms of image reconstruction method were proposed, such as Back-projection method, Iterative method, Analytic method[3]. And there are two sorts of methods in the Back-projection method, that is Filtered back-projection method and Fourier reconstruction method. And the Filtered back-projection method is also called Convolution method or Fourier filtering method[3].

2. Beam hardening effect

The beam hardening effect is the origin of the error which is the systematic, unavoidable and peculiar to the X-ray CT scanner. The beam hardening effect is resulted from the preferential absorption of the low-energy portion of the X-ray beam spectrum as it traverses an object.

X-rays keep relatively high proportion of high energy portion of the spectrum after they are attenuated in an object. Then the profile of a reconstructed image has concave feature just as it is on the surface of a concave lens in the case of an object with uniform density, such as the water schematically shown in Fig. 2. The effect is also called "cupping effect" being resulted from the feature of the shape illustrated in Fig.2(c). The beam hardening theoretically never occurs in the case of monochromatic X-rays. In the case of continuous X-rays the effect unavoidably occurs.[2,3]

All the medical CT scanners have some types of beam hardening correction method. The most expensive method is to use the dual-energy pre-reconstruction processing[12]. There are two types of correction methods which have been generally adopted in CT scanners. The one is the method of addition some filters such as metal plates in order to cut off the low energy parts. The other is to use the software. Non-linearity in the traverse-distance depending on the intensity of X-rays was calibrated with values picked up from the data table for the correction. The correction data table had been previously obtained with standard materials.

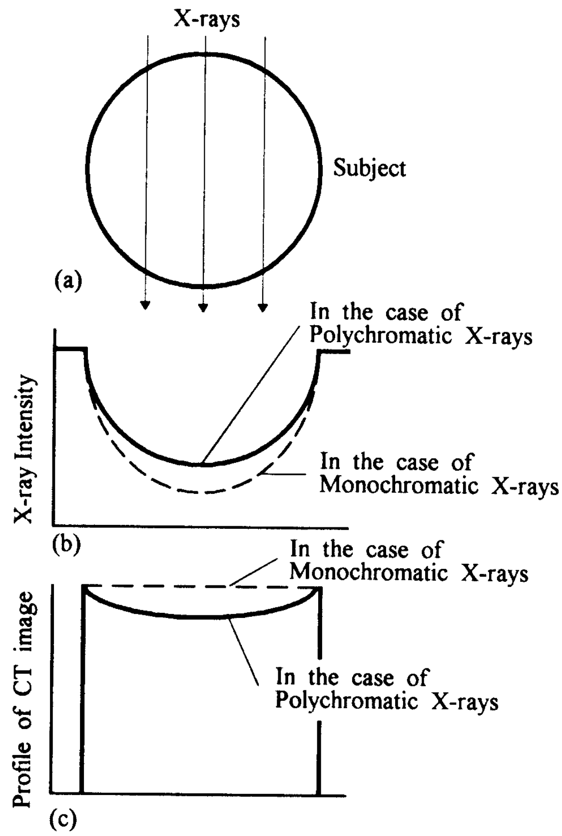

Fig. 2. Schematic diagram explaning the beam hardening effect.

The method of additional filter was generally used on medical CT scanners. And also a compensation materials such as water bags, which were attached to around an object, were used in many cases[7].

In this study a software was developed for the correction of the beam hardening effect. The method of adding a filter was not adopted for the reconstruction of images, because as much lower energy parts of X-rays as possible to be obtained was utilized.

Materials and Methods

1. Method of computer simulation

An attenuation of X-rays was calculated with typical materials. The object was a cylindrical material filled with water. The diameter was 3 centimeters.

There are some materials between the X-ray source and the detector in the system; namely beryllium which is attached at the window of X-ray tube, and aluminum of detector's cover which is necessary for protecting the semiconductor in the detector. The spectrum of X-rays attenuated with the materials is calculated with the equations listed in the previous section. The energy dependence of the materials is obtained with the linear regression analysis listed in the data books on radiology.[5,10] The obtained regression equations were as follows.

$$\left.\begin{aligned} D_W(E) &= 1.787 \cdot 10^3 \cdot E^{-2.553} \\ D_a(E) &= 1.690 \cdot 10^3 \cdot E^{-2.512} \\ D_b(E) &= 5.741 \cdot 10 \cdot E^{-1.431} \end{aligned}\right\} \quad (9)$$

The materials used in the simulation are as follows. The target in the X-ray tube is assumed to be made with tungsten. In general, the target in the X-ray tube is tungsten. The window plate in the X-ray tube is made of the beryllium of 0.5 millimeter thickness. The cover of detector is made of the aluminum plate of 0.2 millimeter thickness. The energy spectrum is calculated in the case when traverse distance is fixed to be from 5 to 30 millimeters. The source voltage is fixed at 50kV.

2. Algorism

A Filtered back-projection method was used for reconstructing images in this study. The projection data from the respective angles were calculated with superposition-integral calculus, using correction function g(k), and then the data were back-projected to the two-dimensional distribution of the linear X-ray attenuation coefficients f(x,y).

Ramachandran's correction function was used as a correction function. Ramachandran's correction function was expressed as follows in the case when interval was 1[8].

$$G(k) = \begin{cases} 0 & (k \neq 0 \text{ and in even number case}) \\ 1/4 & (k=0) \\ -(1/\pi k)^2 & (k \text{ is odd number case}) \end{cases} \quad (10)$$

Computer program developed in this study was based on the FORTRAN program published by A.Rodney and Giovanni Di Chiro[8]. And C language was used to describe the program. The List on the main parts of the computer program was shown in the Appendix for the convenience. The program was described with C language which could be compiled with "Turbo C ver. 2.0" provided by Borland International Co.Ltd.

3. Instrument

(1) System Configuration

The configurations of projection and rotation in the scanner are illustrated in Fig. 3. The X-rays are projected vertically, and a subject is rotated with the horizontal axis. The system diagram is shown in Fig. 4.

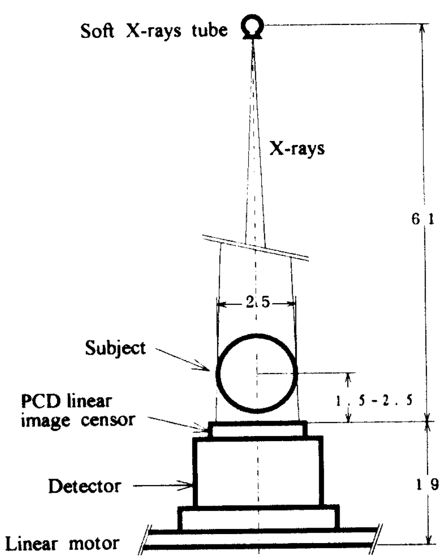

Fig. 3. The projection system of the soft X-ray CT scanner (unit: cm).

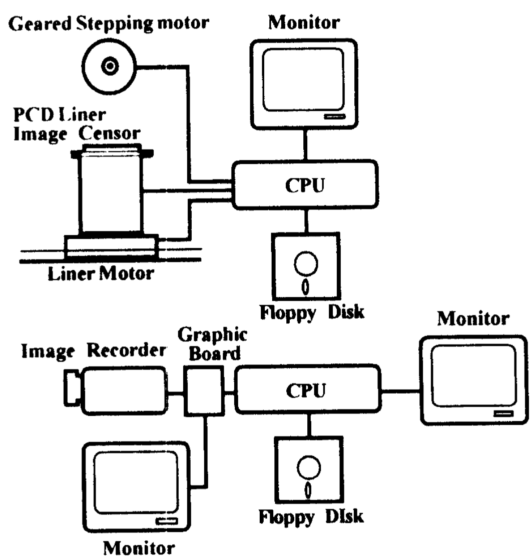

Fig. 4. Acquisition of projections and reconstruction system.

The specifications of the scanner are as follows. The dimension of objects is within 45 millimeters. Selection can be made between the two kinds of the scanning methods. The one is the method of the second-generation (shift and rotation), the other is that of the third-generation (rotation only)[3]. Detector has 512 elements of a sensing array in the span of 25.4 millimeter. The outputs from the detector are digitized and recorded during the half-rotation of the subject with an interval of 1 degree. Then, 180 views of one dimensional image are obtained in a set. The set of data are used for the reconstruction (back-projection) process to the two dimensional distribution of the X-rays absorption coefficient. The computation of the back-projection is executed with a desktop computer. The reconstructed images have 256 ×256 discrete picture elements. The reconstructed images are displayed on a monitor through the full-color graphic board (Nisca Co. Ltd.).

(2) X-rays source, Detector and Driver

The soft X-ray apparatus (SOFTEX Co. Ltd., CMBW-2) with a cooling unit was used as the X-rays source. The maximum source voltage was 60kVp, and the maximum source current was 30mA.

The linear image sensor arrayed the plasma-coupled devices (PCD, Hamamatsu Photonics Co. Ltd.) as the X-rays detector. The PCD linear image sensor had 512 individual photodiodes as a linear array. The outputs from the PCD were processed with 16-bit analog-to digital converter(C2890, Hamamatsu Photonics Co. Ltd.)

The sample was rotated 180 by degrees with the interval of 1 degree being driven by the stepping geared motor during the acquisition of one set of data. The PCD was translated with a liner pulse-motor (THK Co. Ltd.) in case of a large sample, during the data acquisition.

(3) Materials

Okra (*Hibiscus esculentus L.*) and Buna (*Fagus crenata* BLUME, 15×15 millimeter) were used as a plant and a wood samples for demonstrating the ability of the CT scanner. Four kinds of plastics column were used for evaluating the density resolution; such as Polypropylene (density: $\rho=0.905$), Polyethylene ($\rho=0.953$), Nylon ($\rho=1.129$), Acrylic resin ($\rho=1.189$). The diameter of each column is 20 millimeters.

Results and Discussion

1. Simulation results

The simulation results for the energy spectrum of the continuous X-rays were shown in Fig. 5. The traverse distances in water were changed from 5 millimeters to 30 millimeters with 0.5 millimeter step. The photodiode in the detector receives larger amount of the X-rays according to the longer traverse distance. It is clear that the longer is the distance in water the higher is the energy spectrum of X-ray.

The projected data through a subject with some materials in the system, can be calculated with equation (7). The simulated projection data are plotted as solid circles in Fig. 6. The projection data have non-linear relationships with the traverse distance in water. The open circle has been corrected by data as in the following.

The liner relationship between the projected data and the distances was obtained in the order of the 1.35 power up to 30 millimeters. The correction method was quite simple for practical purposes.

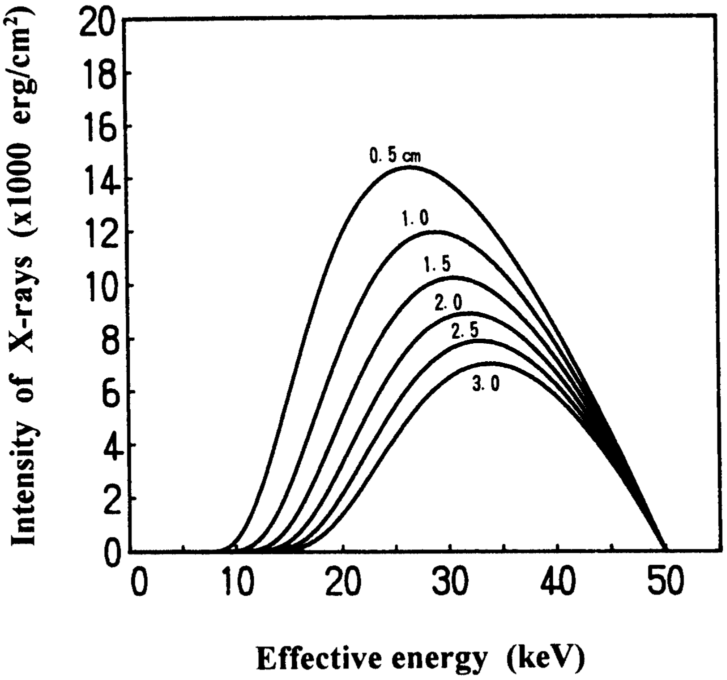

Fig. 5. The results of computer simulation. The figure represents the traverse distance.

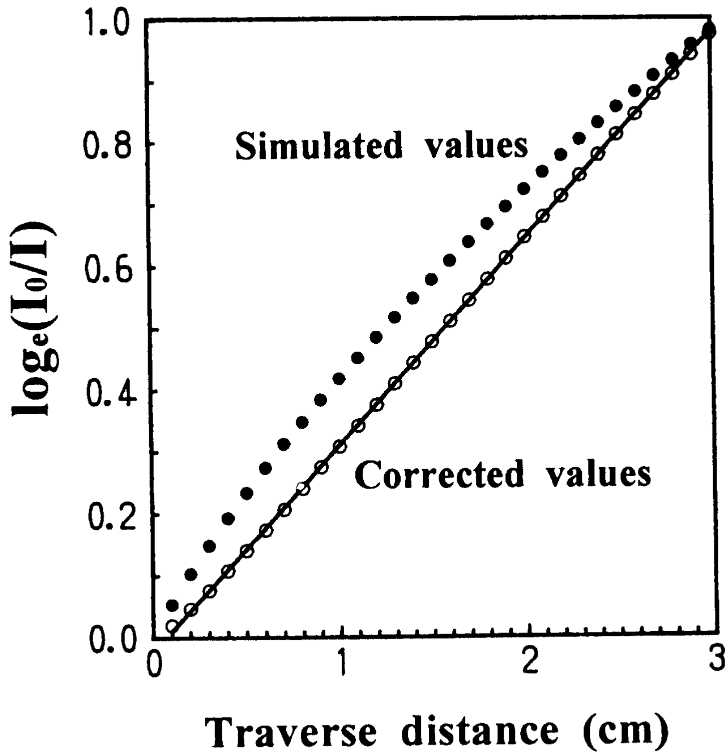

Fig. 6. The simulated values (solid circle) and their corrected values (open circle) in the case of continuous X-rays absorbed in water with any traverse distances.

2. Reconstructed Images

Fig. 7～9 show the reconstructed images of cross section for a demonstration. Fig. 7 shows a cross section of Okra. The source voltage was 50kV, the source current was 10mA, and the accumulation time for the PCD per a view of one projection was 500 milliseconds. The inner structure was clearly described in detail without destruction. Fig. 8 shows a cross section of Buna as a typical wood example. The annual rings and broad rays were clearly distinguished. Some satisfactory results can be obtained with the original soft X-ray CT scanner. More work is required to evaluate mathematically the spatial resolution of the CT image, using the modulation transfer function.

Fig. 7. The CT image of Okra. The source voltage is 50kV, the source current is 10mA, and accumulation time of PCD is 500mSec.

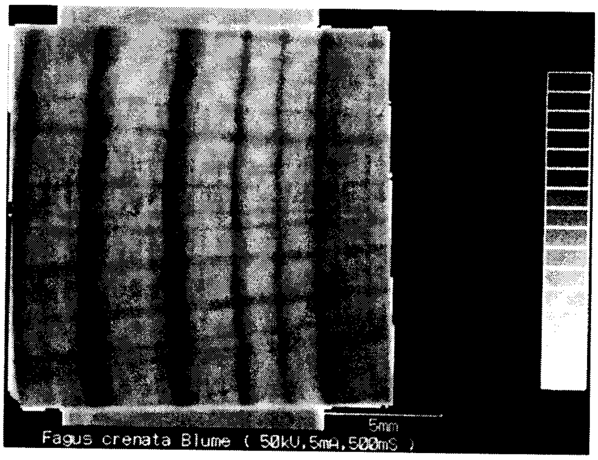

Fig. 8. The CT image of Buna. The source voltage is 50kV, the source current is 5mA, and accumulation time of PCD is 500mSec.

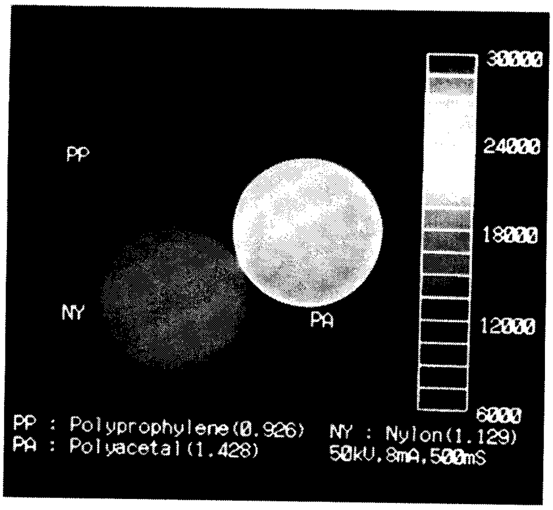

Fig. 9. The CT image of plastics column. The source voltage is 50kV, the source current is 8mA, and accumulation time of PCD is 500mSec.

3. Density resolution

The density dependence of CT-value obtained by the system was shown in Fig.10. The standard deviation and coefficient of variance obtained from the CT-values in the region near the center of each plastic material, were shown in Table 1. The number of pixels used for respective calculations were 709. By the way, the CT-values described in this paper were not in possession of the same meaning as the CT-number defined in the medical CT scanners[3].

The CT-values could be converted into density, using the result shown in Table 1. Then, the mean of the double of the standard deviations was equivalent to the density of 0.0042 g/cm^3. The accuracy was reported to have been as much high leveled as the accuracy estimated with well calibrated medical CT scanners[1].

The accuracy of the estimation of the moisture content in wood, depends on the density of the wood, because the moisture content is calculated basing on the oven-dried weight. The accuracy of the estimation of the moisture content distribution made by the scanner is only 1 percent of moisture content in the case of wood whose density is 0.42 g/cm^3.

The scanner has a superior capacity for estimating the density and moisture content dis-

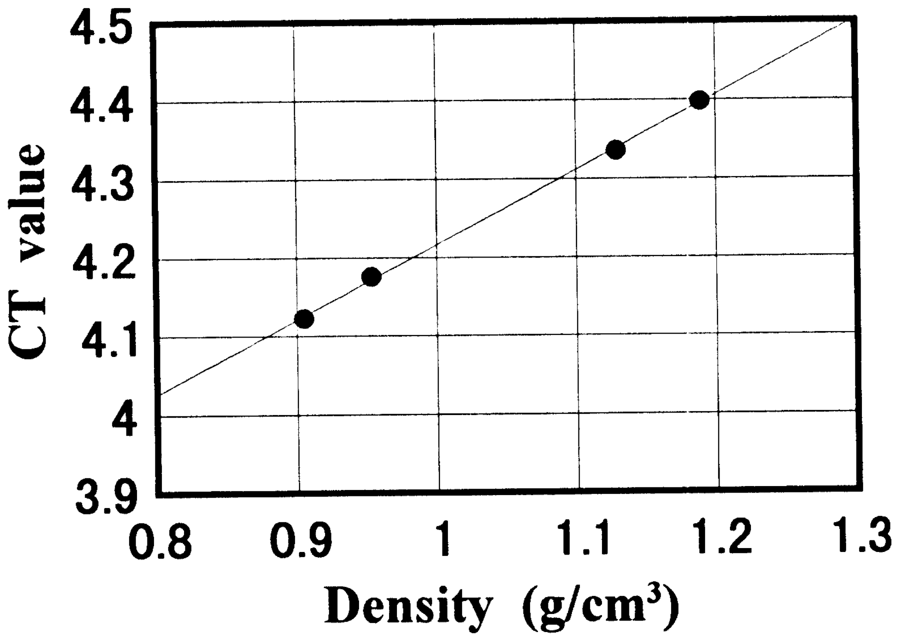

Fig. 10. The relationship between CT values and density of four kinds of plastics.

Table 1. Density of four kinds of plastics obtained from CT images

Plastics	PP*1	PE*2	NY*3	AR*4
Density(g/cm^3)	0.905	0.953	1.129	1.189
Means	4.1226	4.1757	4.3358	4.3981
Standard Deviation	0.0015	0.0016	0.0015	0.0015
Coefficient of Variation (%)	0.0362	0.0376	0.0342	0.0334

Each value was calculated with 709 pixels near the center of each plastic image.
*1:Polyprophylene, *2:Polythylene, *3:Nylon, *4:Acryl.

tribution in wood as mentioned above. It is hoped that the scanner is going to be practical and useful for the non-destructive measurements on density and moisture content distribution in bio-materials, such as woods and plants.

Conclusions

The original soft X-ray CT scanner was developed. Some techniques were proposed through the study. The results obtained were as follows.

1. A simple correction method for the beam hardening effect was proposed. The soft X-ray CT scanner was actually installed, using the proposed correction method.
2. A linear relationship between the logarithm of the reconstructed value and the densities of four kinds of plastics was obtained. The standard deviation of the respective plastics was 0.0015, and coefficient of variation was in the range of 0.033 to 0.038 percent.
3. The accuracy of estimation of density was 0.0042 g/cm^3 in case of the soft X-ray CT scanner. The scanner enabled us to estimate the distribution of moisture contents in woods, whose specific gravity was 0.42, with the accuracy of 1 per cent of moisture content.

The developed soft X-ray CT scanner was quite useful in the non-destructive measurement of density distribution in bio-materials, organic materials, to say nothing of woods and plants.

More work is required to evaluate the spatial resolution of the CT images obtained by the soft X-ray scanner, using the modulation transfer function.

Acknowledgements

The authors express the appreciation for the support from K. Koizumi (SOFTX Co. Ltd.). He lent us the apparatus of the soft X-ray source for this study.

References

1) Endo, M. and Iinuma, T.: A simulation study by digital computer on reconstruction of X-ray transaxial tomography using convolution methods, Iyoudenshi to seitaikougaku. **15**, 334-341 (1977) (in Japanese with English Summary)

2) Hattori, Y. and Kanagawa, Y.: Non-destructive measurement of moisture distribution in wood with medical X-ray CT scanner I, *Mokuzai Gakkaishi*, **31**, 947-982 (1985) (in Japanese with English Summary)

3) Iwai, Y.: CT scanner, Koronasya, Tokyo (1981) (in Japanese)

4) Lindgren, L.O.: Medical CAT-scanning: X-ray absorption coefficients, CT-numbers and their relation to wood density. *Wood Sci. Technol.*, 25, 341-349 (1991)

5) Murakami, U., Danno, T. and Kobayashi, M.: Databook of radiation. p.333-342 Chujinsyokan, Tokyo, (in Japanese)

6) Onoue, M.: Non-destructive Measurement Technology. p.5-32 Asakurasyoten, Tokyo (1990) (in Japanese)

7) Persson, S. and Ostman, E.: Use of computed tomography in nondestructive testing of polymeric materials, *Applied Optics*, **24**, 4095-4104 (1985)

8) Rodney, A.B. and Giovanni, D.C.: Theory of image reconstruction in computed tomography.

Radiology, 117, 561-572 (1975)

9) Taguchi, I.: X-ray computed tomographic scanner for non-medical use, *Bunseki*, 511-515 (1987) (in Japanese)

10) Tanaka, H and Ozaki, T: Technique and experiment on radiology: basic, 2nd Kyoritsusyuppan, Tokyo (1990) (in Japanese)

11) Wagner, F.G., Tayler, F.W., Ladd, D.S., McMillin, C.W and Roder, F.L: Ultrafast CT scanning of an oak log for internal defects. *Forest Product Journal*, 39, 62-64 (1989)

12) Wellington,S.L. and Vinegar, H.J.: X-ray computerized tomography. *J. Petroleum Technology*, August, 885-898 (1987)

Appendix

```
/* Reconstruction Program for Soft X-ray CT scanner */
#include <stdio.h>
#include <stdlib.h>
#include <alloc.h>
#include <graphics.h>
#include <math.h>
#include "a:¥tc¥gopen.h"
#define JE 256
#define JEE 255
#define K 180
unsigned int  mn[JE], mx[JE] *ia[K], base[JE], b[JE];
long     *ib[JE];
double ff[JE+1], fmax, ibmax, divi=10000.0, divi2=10000.0, ia_mean=0;
char    filename[25], writename[25], basename[25];
FILE *fp;
main (argc,argv)
int argc;char *argv[];
{   int i, j, k, jk, ir, j0, ix, ii, jj, m, i1, ii1, i2, ii2;
    unsigned long int aa[JE], a1, a2, a3;
    long int iz, iia, c, r;
    float q, xia, xx, xi, l, k1;
    double sn, cs, th[K+1], ro, xd, bs_ia;
    double max_ia=0.0, min_ia=60000.0, max_bs=0.0, min_bs=60000.0;
    char s,chr();
        strcpy(filename,"C:¥¥DATA¥¥"); strcat(filename,argv[1]);
        strcpy(basename,"A:¥¥TC¥¥DATA¥¥"); strcat(basename,argv[2]);
        strcpy(writename, filename); strcat(writename,".135");
        gopen(); allocate_m(); read_data(); read_base();
        printf("filename=%s%d ", filename,argc);
        printf("basename=%s ¥n", basename);
        printf("writename=%s ¥n", writename);
    i=6; for(k=0;k<K;k++) {ia_mean=ia_mean+ia[k][i];} ia_mean=ia_mean/180.0;
    for(k=0;k<K;k++) {for(i=6;i<JE-6;i++) {
                        if(min_ia>ia[k][i]) {min_ia=ia[k][i];}
```

```
                        if(max_ia<ia[k][i]) {max_ia=ia[k][i];}}}
for(i=6;i<JE-6;i++) {if(max_bs<b[i]) {max_bs=b[i];}
                        if(min_bs>b[i]) {min_bs=b[i];}}
bs_ia=min_ia/max_bs;
printf("max_bs=%5.0f ", max_bs);printf("min_ia=%5.0f ", min_ia);
printf("bs_ia=%5.3f ¥n",bs_ia);
printf("min_bs=%5.0f ", min_bs);printf("max_ia=%5.0f ¥n", max_ia);
for(i=0;i<JE;i++){b[i]=b[i]*bs_ia;} max_bs=max_bs*bs_ia;min_bs=min_bs*bs_ia;
k=0;for(i=2;i<JE;i++) {
   i1=i; if(ia[k][i]<=max_ia*0.7)break;}
k=K-1;for(i=JE-13;i>1;i--) {
   i2=JE-i+2;if(ia[k][i]<=max_ia*0.7)break;}
m=0;if(i1>i2) {m=i1/2.0-i2/2.0;}
   if(i1<i2) {m=i2/2.0-i1/2.0;}
printf("i1=%d i2=%d m=%d ¥n",i1,i2,m);
setcolor(7);line(300,370,300+JE,370); line(300,370,300,370-250);
                      line(556,370,556,370-250);line(428,370,428,370-300);
                      line(128,370,128,370-300);setcolor(6);
                      line(300+i1,370,300+i1,370-250);line(556-i2,370,556-i2,370-250);
                      line(i1,370,i1,370-250); line(256-i2,370,256-i2,370-250);
setcolor(7);
for(k=0;k<K;k++) {
  if(i1<=i2) {for(i=JE-1;i>m+1;i--) {ia[k][i]=ia[k][i-m];}
                      for(i=m+1;i>=0;i--) {ia[k][i]=ia[k][1];}}
  if(i1>i2) {for(i=0; i<JE-m;i++) {ia[k][i]=ia[k][i+m];}
                      for(i=JE-m;i<JE;i++) {ia[k][i]=ia[k][2];}}
}
if(i1<=i2) {for(i=JE-1; i>m+1; i--) {b[i]=b[i-m];}
                      for(i=JE-m+1;i<JE; i++) {b[i]=b[1];}}
if(i1>i2) {for(i=0; i<JE-m;i++) {b[i]=b[i+m];}
                      for(i=JE-m;i<JE; i++) {b[i]=b[2];}}
for(k=0;k<K;k++) {for(i=1;i<JE-12;i++) {ib[k][i]=max_ia-ia[k][i];}}
for(k=0;k<K;k++) {for(i=1;i<JE-12;i++) {ia[k][i]=ia[k][i]-(b[i]-min_bs);}}
max_ia=max_ia+(max_bs-min_bs);
for(k=0;k<K;k++) {for(i=1;i<JE-12;i++) {
   xd=ia[k][i]; xd=log(max_ia/xd); ia[k][i]=pow(xd,1.35)*divi2;
   putpixel(i+300,370-ia[k][i]/200-k,7);
} for(i=JE-12;i<JE;i++) {ia[k][i]=0;}
}
for(k=0;k<K;k++) {for(i=1;i<JE-12;i++) {
                        putpixel(i,370-ib[k][i]/200-k,7);}}
for(i=0;i<JE;i++) {putpixel(i,390-(b[i]-min_bs)/10,7);}
for(j=0;j<JE;j++) {for(i=0;i<JE;i++) {ib[i][j]=0;}}
jk=0;fmax=0.0;k1=3.1415927*K;
for(i=0;i<K;i++) {jk++;xi=jk;th[jk]=3.1415927*xi/K;}
```

```
   c=(JEE+1)/2;r=(JEE-1);r=rr */4;
   for(j=1;j<JE;j++) {ro=r-(c-j)*(c-j);
                        ro=sqrt(ro);ir=ro;mn[j]=c-ir;mx[j]=JEE+1-mn[j];}
   for(k=0;k<K;k++) {printf("%4d",k);
      sn=sin(th[k+1]);cs=cos(th[k+1]);ff[JE]=0.0;
      for(i=1;i<JE;i++) {
                  q=ia[k][i]*2.4674011;j0=(1+i)%2;
                  for(j=j0;j<JE-1;j=j+2) {xia=ia[k][j];q=q-xia/((i-j)*(i-j));}
                  ff[i]=q/kl;
      }
      for(j=1;j<JE;j++) {xx=c+(c-j)*sn+(mn[j]-c-1)*cs;
            for(i=mn[j];i<=mx[j];i++) {
                  xx=xx+cs;ix=xx;
                  ib[i][j]=ib[i][j]+(ff[ix]+(xx-ix)*(ff[ix+1]-ff[ix]))*10000;}
            for(i=mn[j]+10;i<=mx[j]-10;i++) {if(ib[i][j]>ibmax) {ibmax=ib[i][j];}}
   }   }
   for(j=1;j<JE;j++) {
      for(i=1;i<JE;i++) {
            xx=(ib[i][j]-ibmax/2);xx=xx/(ibmax/2);iz=xx*0xe+1;
            if(iz>=0) {putpixel(i,j,iz);}
   }}
   printf("ibmax=%f¥n",ibmax);
   write_data();return;
}
allocate_m() {
    int i;
    printf("(1)%lu bytes free ",farcoreleft());
          for(i=0;i<K;i++) {if((ia[i]=(unsigned int*) malloc(JE*sizeof(int)))==NULL)
       {perror("Insufficient memory for ia");exit(1);}}
    printf("(2)%lu bytes free ", farcoreleft());
    for(i=0;i<JE;i++) {if((ib[i]=(long*)malloc(JE*sizeof(long)))==NULL)
       {perror("Insufficient memory for ib"); exit(1);}}
    printf("(3)%lu bytes free¥n", farcoreleft());return; }
read_data() {
    if((fp=fopen(filename,"rb"))==NULL) {
       perror("Can not open the file");exit(1);}
    read_plane();fclose(fp);return; }
read_plane() {
    int i, j, k; double dd;
    unsigned int buffer[256];
    for(k=0;k<K;k++) {          /*0 to 180 step 1  */
       fread(buffer,sizeof(int),256,fp);
       for(i=0;i<256;i++) {ia[k][i]=buffer[i];}
    }
    for(k=0;k<K;k++) { /*Volt */
```

```
        for(i=0;i<256;i++) { dd=ia[k][i];
                             ia[k][i]=dd*10.0/65536.0*10000.0;}
    } return; }
read_base()
{   int i;
    if(( fp=fopen(basename,"rb"))==NULL)
     { perror("Can not open then the file");exit(1);}
    read_base_plane();fclose(fp);return; }
read_base_plane() {
    int i, j, k; unsigned int buffer[256]; double dd;
    fread(buffer, sizeof(int), 256, fp);
    for(i=0;i<JE;i++) {b[i]=buffer[i];}
    for(i=0;i<JE;i++) {dd=b[i];b[i]=dd*10.0/65536.0*10000.0;} return; }
write_data() {
    int i;
    if((fp=fopen(writename,"wb"))==NULL) {
       perror("Cannot open the file");exit(1);}
    write_plane();fclose(fp);return; }
write_plane() {
    int i, j, k, l, m;
    unsigned int buffer[JE];
    float d;
    buffer[0]=ibmax/100;buffer[1]=ia_mean;
    for(i=2;i<JE;i++) {buffer[i]=0;} fwrite(buffer, sizeof(int), JE, fp);
    for(j=1;j<JE;j++) {buffer[0]=0;
       for(i=1;i<JE;i++) {
             if(ib[i][j]<0) {ib[[i][j]=0;}
             d=ib[i][j]: d=(d/ibmax*30000);k=d;buffer[i]=k;
             k=(d/30000*6)+1;
             putpixel(i+260, j, k);
       }
       fwrite(buffer,sizeof(int), JE, fp);
    }
    printf("¥n"); return; }
char chr(code)
int code; { return((char)code); }
```