X-Ray Beam-Width Limiting Device[1]

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1 Background

The Lodox Statscan system (Fig. 1) utilizes an X-ray fan beam and employs linear slot-scanning radiography [1]. To precisely expose the region of interest with X-rays during scanning, the beam-width is collimated with sliders, driven on a toothed belt by servo motors, thereby adjusting the size of the slot through which the X-ray beam is transmitted. However, these sliders sometimes stall during horizontal C-arm scanning because of the effect of gravity and also often stop abruptly when they reach end of travel, which can damage the motors, the belt, or the sliders. Furthermore in the event of abrupt power supply loss while scanning, the current mechanism needs to be reinitialized in order to relocate the position of the beam-limiter blocks. The aim was therefore to develop an alternative X-ray beam-width limiting mechanism that is more reliable in both vertical and horizontal orientations, with soft stops should the beam-limiter blocks reach end of travel, and to maintain a record of the position of the beam-limiter blocks in case of abrupt power supply loss.

2 Methods

The new mechanism consists of two beam-limiter blocks to adjust the width of the slot, high torque motors that are able to move the blocks in both the vertical and horizontal orientations of the C-arm (Fig. 1), and beam-limiter block position monitoring by means of high-precision sonar sensors. The entire mechanism fits into the space available within the housing on the C-arm (500 × 180 × 100) mm^3.

Each beam-limiter block consists of a 3 mm thick lead layer, sandwiched between two aluminum layers (Fig. 2). The lead attenuates the X-rays while the aluminum provides mechanical support. It can be shown that the 3 mm lead layer attenuates 99.85% of a 140 keV X-ray beam

$$I = I_O \ell^{-\mu \cdot k}$$

where I_0 is the total initial energy in keV, μ is the attenuation coefficient of lead (2.18/mm [2]), I is the transmitted energy in keV, and k is the thickness of the lead in mm. An interlocking mechanism completely closes the gap between the blocks.

The position of the blocks is controlled using a stepper motor and a leadscrew mechanism (Fig. 3). The leadscrew mechanism converts rotational movement into linear motion [3], thereby moving the beam-limiter blocks back and forth. The leadscrew arrangement has an 8 mm diameter and a 2 mm pitch.

The torque required to move the beam-limiter blocks in the vertical and horizontal orientations was calculated using the leadscrew equations for the translation of rotary motion to linear motion [4]

$$T_h = \frac{Fl}{2\pi\eta} \quad T_v = \frac{Fd}{2}\left[\frac{1+\pi\mu d}{\pi d - \mu l}\right]$$

where F is the load in N, l is the pitch in mm, η is the efficiency, d is the mean diameter of the screw, and μ is the coefficient of friction.

The torque required to move the beam-limiter blocks in the horizontal direction (T_h) is 4.34 N·mm and in the vertical direction

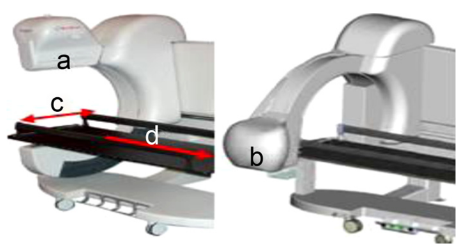

Fig. 1 Lodox Statscan imaging system: (*a*) C-arm in vertical orientation, (*b*) C-arm in horizontal orientation, (*c*) scan width, and (*d*) scan direction

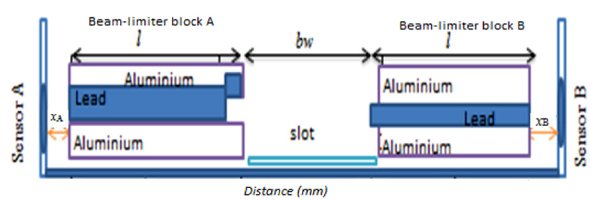

Fig. 2 Two interlocking beam-limiter blocks on either side of the X-ray slot, with ultrasonic distance sensors placed at the extreme end of travel limits

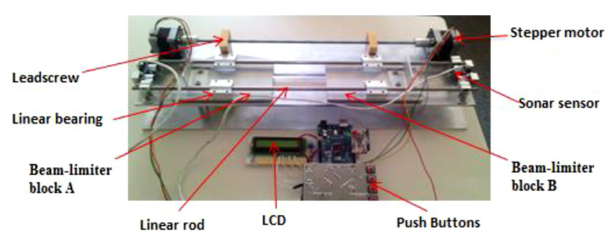

Fig. 3 Prototype beam-width limiter

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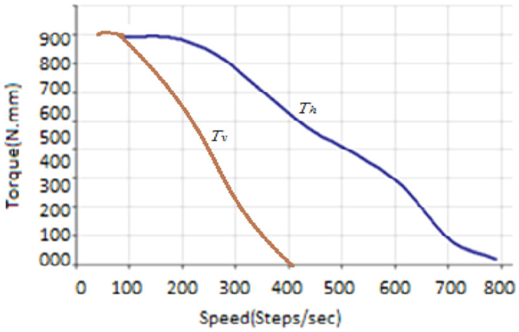

Fig. 4 Torque variation with speed (Tv) vertical orientation and (T_h) horizontal orientation

(Tv) it is 6.40 N · mm ($F = 3.07$ N, $l = 2$ mm, $\eta = 98\%$, $\mu = 0.1$, and $d = 8$ mm). The 200 steps per revolution motor has a minimum holding torque of 40 N·mm, which is sufficient to move the beam-limiter blocks in both the vertical and horizontal directions.

LABVIEW professional development toolkit was used to simulate torque variation with speed (Fig. 4). By increasing the motor speed, the motor produced less torque in both the vertical and horizontal orientations. For the same amount of torque, lower speeds were required in the vertical orientation as compared with those in the horizontal orientation. Maximum torque (900 N·mm) was obtained when the motor speed was between 50 and 100 steps/s and 100–200 steps/s for vertical and horizontal orientations, respectively. A potentiometer was used to vary the motor speed.

High accuracy sonar sensors (±0.05 mm) [5] were used to locate the position of each block and compute the X-ray beam-width, which is simultaneously displayed on the LCD. The sonar sensors are ultrasonic transducers that emit a high-frequency sound wave and detect the reflected sound wave in the form of an echo. The time interval between emitting the sound wave and detecting the echo was used to determine the distance of the beam-limiter block from the sensor (x_A and x_B in Fig. 2).

At any given time t, the position of the slot-side edge of each block can be calculated as $(l + x_A)$ mm or $(l + x_B)$ mm, respectively, where l is the length of a block. The beam-width (bw, see Fig. 2), as determined by the slot distance between the blocks, is also displayed on the LCD (Fig. 3). When the distance between the two blocks is less than 20 mm, a trigger signal is sent to the stepper motors to reduce their speed and the motors are gradually brought to a stop when the distance between the blocks is 1 mm, thereby preventing direct contact between the beam-limiter blocks.

Motor speed is also reduced when the beam-limiter blocks approach their end of travel (x_A or x_B less than 20 mm). The motors are stopped when either x_A or x_B is less than 10 mm, thereby preventing direct contact between the beam-limiter blocks and the sonar sensors.

3 Results

Figure 5 shows motor speed plotted against beam-width, obtained using LABVIEW. The motor speed, for a beam-width greater than 20 mm, can be set using a potentiometer.

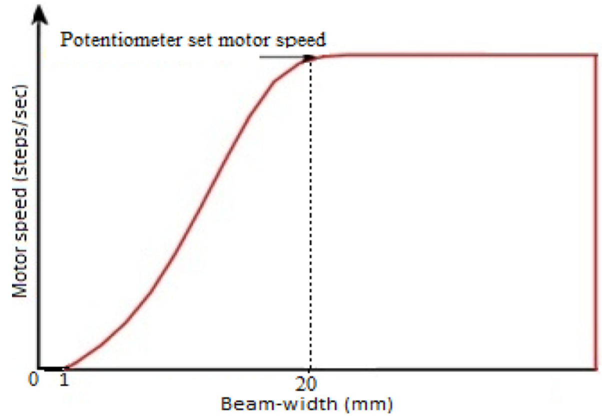

Fig. 5 Motor speed variation with beam-width

The soft stops are an improvement over the current mechanism which utilizes current overload to stop the motor when the beam-limiter blocks come into contact with one another.

In the event of power failure, the leadscrew mechanism ensures that the beam-limiter blocks remain stationary. When power is restored, the sensors instantaneously determine the position of the beam-limiter blocks. In the old, potentiometer-based positioning system it was necessary to move the blocks back to their starting position and then reacquire the slot distance, a process that takes approximately 13 s to complete.

4 Interpretation

An X-ray beam-width limiting mechanism to regulate the X-ray beam-width in both the vertical and horizontal orientations of the Lodox Statscan C-arm was designed. The mechanism is able to drive the beam-limiter blocks in both vertical and horizontal orientations with the use of a leadscrew mechanism. A sonar sensor was used to monitor the block position. These sensors produce sufficiently accurate measurements under both steady and interrupted power supply. The soft stopping function has the potential to reduce motor failure, hence reducing maintenance costs and making the device more reliable.

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