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Computer-Aided Design Of Brakes

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Abstract— In this work, computer software that is user-friendly for the analysis and design of brakes was developed. This was done using Microsoft Visual Basic object-oriented programming language. In designing the software, the various classes of brakes were considered. The mathematical expressions that govern the relationship between force, torque, pressure, heat generated rate and energy were assembled and carefully programmed. To enhance the ability to visually display and interpret solutions, graphical features were incorporated in the software. A spectrum of benchmark problems were used to test the software's robustness, accuracy and efficiency. The results show that the software is highly accurate, efficient and robust. The usage of the software greatly increases the accuracy, and reduces the complexity and time spent in the analysis and design of brakes.

Index Terms — Object-oriented programming, Brake, Torque, Force, Heat generation and dissipation, Computer- aided-design

Notation

A_c contact area, m^2
A_r radiating surface area, m^2
a_1 distance from centre of drum to pivot, m
a_3 distance from F_2 to shoe pivot (hand brake), m
b_1 distance from point of application of force to shoe pivot, m
b_2 distance from F_1 to the shoe pivot (hand brake), m
C_1 constant (external shoe brake)
C_2 coefficient of heat transfer, W/m^2k
c_1 distance from point of application of normal force to the shoe pivot (external shoe brake), m
c_2 moment arm of the actuating force (external shoe brake), m
c_3 distance from the point of application of force to the shoe pivot (hand brake), m
E_k total kinetic energy absorbed, W
E_p total potential energy absorbed, W
e natural logarithm base
F force applied to the brake shoe, N
F_1 tension on the right side, N
F_2 tension on the slack side
F_L force applied to the left block of the brake, N
F_R force applied to the right block of the brake
H_b heat generation rate,, W
M_f moment of frictional forces with respect to the shoe pivot (right shoe), Nm
M_f' moment of frictional force with respect to the shoe pivot,(left shoe), Nm
M_n moment of normal forces with respect to the shoe pivot (right shoe), Nm
M_n' moment of normal forces with respect to the shoe pivot,(left shoe), Nm
N normal force on the shoe brake, N
N_L normal force on the left shoe brake,, N
N_R normal force on the right shoe brake, N
P_{av} average pressure, N/m^2
$P_{m,}$ maximum pressure (right shoe), N/m^2
P_m' maximum pressure (left shoe), N/m^2
R internal radius of drum (external shoe brake), m
T torque, Nm
V peripheral velocity of drum, m/s
f coefficient of friction
h distance from center of drum to the pivot, m
r internal radius of drum (internal shoe brake), m
w face width of shoe, m
α angle of wrap of belt, degrees
Δt temperature difference between exposed radiating surface and the surrounding air(degree centigrade or Kelvin)
θ angle of contact (degrees)
θ_1 center angle from shoe pivot to heel of lining (internal shoe brake), degrees
θ_2 center angle from shoe brake to toe of lining (internal shoe brake), degrees
θ_m center angle from shoe pivot to point of maximum pressure, degrees

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I. Introduction

The design of brakes involves evaluating the force, pressure, torque, heat-generated, heat dissipated and the coefficient of friction. When in use, the energy absorbed by brakes in the process of slowing down or stop moving part(s)) is dissipated as heat. In the area of brake design, a number of researchers have contributed towards the advancement of the process. One such contribution was from Fazekas; who significantly reduced the difficulty associated with numerical integration in the analysis of circular (Bottom or Puck) pad caliper brake, Fazekas [1]. Ferodo [2] and Neale [3] developed a table for the amount of friction material required for a given average braking power.

In the area of developing software for machine design, very little documented research exists. Some of these documented machine design software include the works of Jombo and Adetona [4]; who worked on belts and pulleys. However, efforts have been made recently to develop software for the design of machine elements, using object-oriented programming technique [5, 6]. Some of these works addressed the design of: some types of gears (helical, and spur) see [7, 8], rolling bearings [9], and machine vibrations design [10]. And quite recently, software for the design of Flywheels, was developed and reported, see [11]. Brakes design is well treated in standard machine design texts see refs. [12, 13, 14, 15]. Some commercial software has been developed to design brakes. Most of this software is not robust enough to handle all classes of brakes, while some just consider only electromagnetic brakes, see [16]

The aim of this work is to develop and implement computer software that would greatly facilitate the design of brakes. Consequently in this work we addressed the following engineering design problems [11]: the capability of designing for all brake parameters, reduction of computational complexity and arduous work encountered in brake design, provision of accurate and efficient solutions for brake design process and provision of visual display of program solutions.

II. CLASSIFICATION OF BRAKES

There exist many types of brakes and are generally classified as either external, internal or bond brakes. External shoe brakes are further classified into single and double block shoe brakes. External shoe brakes consist of shoes or blocks which are pressed against the rotating surface of the brake drum. Fig. 1 shows a schematic representation of an external single shoe brake. The design of internal shoe brakes largely depends on force, torque, coefficient of friction and the radius of the rotating drum. Fig. 2 shows a schematic representation of an internal shoe brake.

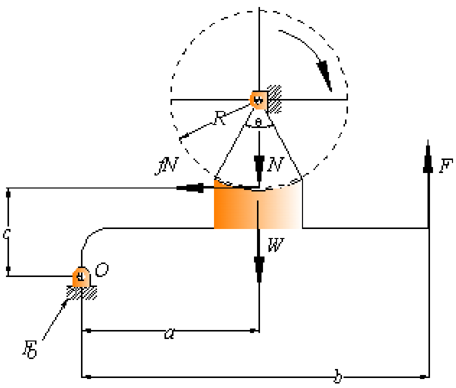

Fig. 1: A schematic representation of an external single shoe brake.

. Band brakes are flexible bands wrapped partly around the drum. Pulling the band tightly against the drum actuates them. The design of band brakes is dependent on force, angle of wrap, coefficient of friction, pressure on the shoes and radius of the drum. A diagram of a simple two way band brake is shown in fig. 3.

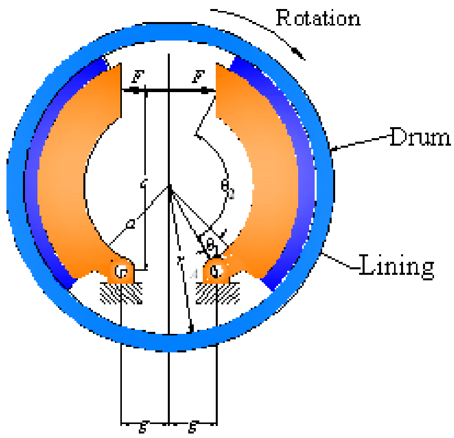

Figure 2: A schematic diagram of internal shoe brake

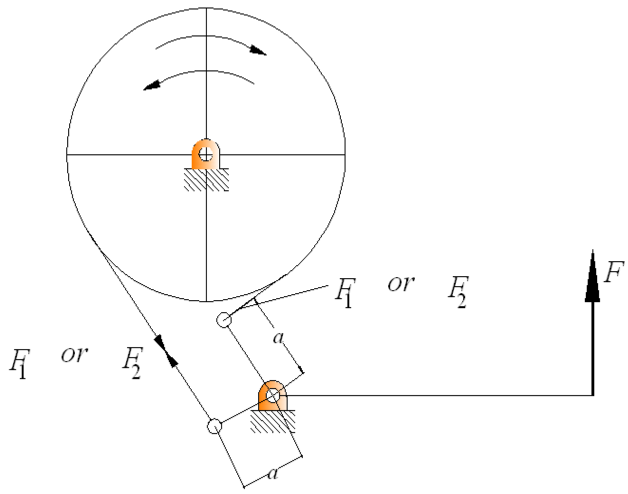

Fig. 3: A simple two way band brake

III HEAT GENERATED

When the brake is actuated, energy is absorbed, which in turn is dissipated as heat energy. This design is dependent on pressure, area of contact, peripheral velocity, coefficient of friction, potential energy, and kinetic energy, coefficient of heat transfer and area of the radiating surface.

IV DESIGN OF THE SOFTWARE MODEL

During the design of the software, the relevant equations (1)-(23)) see refs. [1-3, 12-15] for analyzing the design of brakes shown below were assembled and used to develop the software presented in this work. These design equations were the programmed using Microsoft Visual Basic object-oriented programming language [5, 6]. These fundamental formulae are presented as follows:

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A. External Single Shoe Block Brake Design

For external single shoe brakes the software was developed using the following:
For a clockwise rotation, the actuating force is given by (1)

$$F = \frac{(N+W)a_1 - fNc_1}{b_1} \quad (1)$$

The Braking Torque, when $\theta \le 60^0$, is given by (2). When $\theta > 60^0$, the braking torque is given by (3)

$$T = fNR \quad (2)$$

,

$$T = fNh = fN\left(\frac{(4R\sin\frac{1}{2}\theta)}{(\theta + \sin\theta)}\right) \quad (3)$$

The average pressure is computed using (4):

$$P_{av} = \left(\frac{2C_1\sin\frac{1}{2}\theta}{\theta}\right) \quad (4)$$

Where $$C_1 = \left(\frac{2N}{wR(\theta+\sin\theta)}\right) \quad (5)$$

B External Double Shoe Block Brake Design

For external double shoe brakes the software was developed using (6) – (7)
The braking torque for an external shoe block brake when $\theta \le 60^0$, is given by (6)

$$T = f(N_L + N_R)R \quad (6)$$

When $\theta > 60^0$,, the braking torque is computed using (7)

$$T = fNh = f(N_L + N_R)\left(\frac{(4R\sin\frac{1}{2}\theta)}{(\theta + \sin\theta)}\right) \quad (7)$$

C Internal Shoe Brake Design

The actuating forces are given by (8) – (9)

$$F_R = \frac{(M_n - M_f)}{c_2} \quad (8)$$

$$F_L = \frac{(M'_n + M'_f)}{c_2} \quad (9)$$

Where, M_f and M_n are given by (10) and (11) respectively.

$$M_f = \frac{fp_m wr}{\sin\theta_m}\int_{\theta_1}^{\theta_2}\sin\theta\,(r - a_1\cos\theta)d\theta \quad (10)$$

$$M_n = \frac{p_m wra_1}{\sin\theta_m}\int_{\theta_1}^{\theta_2}\sin^2\theta d\theta \quad (11)$$

$$p'_m = \frac{c_2 F p_m}{M_n + M_f} \quad (12)$$

$$M'_n = \frac{M_n P'_m}{P_m} \quad (13)$$

$$M'_f = \frac{M_f P'_m}{P_m} \quad (14)$$

The braking Torque may be determined using (15)

$$T = fwr^2\left(\frac{\cos\theta_1 - \cos\theta_2}{\sin\theta_m}\right)(p_m + p'_m) \quad (15)$$

V BAND BRAKE

The force in a Band brake is given as shown in (16)

$$F_1 = F_2 e^{f\alpha} \quad (16)$$

The brake Torque in a band brake is computed using (17)

$$T = (F_1 - F_2)r \quad (17)$$

$$F = \left(\frac{F_2 b_2 - F_1 a_3}{C_3}\right) \quad (18)$$

$$P_{av} = \frac{F_1}{wrf\alpha}\left(\frac{e^{f\alpha} - 1}{e^{f\alpha}}\right) \quad (19)$$

VI AMOUNT OF HEAT GENERATED

$$H_g = P_{av} A_c fV \quad (20)$$

$$H_g = E_k + E_p \quad (21)$$

$$H_g = C\Delta t A_r \quad (22)$$

$$H_g = fNV \quad (23)$$

$$H_g = P_{av} A_c fV \quad (20)$$

VII PROGRAMME DESCRIPTION

Microsoft Visual Basic object-oriented programming language was used to design and implement the program. The

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program is structured into three modules as follows: the input stage, the analysis stage and the output stage.

A Input Stage

In this stage, the user provides and enters the basic input parameters of the specific type of brake in the form of data in the respective text boxes of the object interface (form) of the program. The code of the program is written in such a manner that the necessary analyses can be achieved with the entry of minimal number of the basic input parameters.

B Analysis Stage

During this stage, the computer carries out the events initiated by the written code. It processes the data by computing the necessary parameter(s) and stores the result. The result is now ready for the output stage. The speed at which the computer processes the data depends largely on the speed of the microprocessor of the computer.

C Output Stage

This stage involves displaying the processed data numerically as output on the object interface of the program. In this work, the code of the program was written in such a way that the results of the output can be displayed graphically with pre-selected dependent variable versus a pre-selected independent variable.

VIII PROGRAM PSEUDO-CODE ALGORITHM

In developing the software the following algorithm or pseudo code was used

Algorithm

If objectsingleshoebrakedesign1.load = **true, then**
If $\theta \le 60^0$ **then**
Enter known parameters: N, W, a, b, c, f ,
Compute the value of the actuating force using equation 1
Else if known input parameters: f, N, R, θ
Compute the value of torque using equation 2
Beep and note that $\theta \le 60^0$
End if
End if
If objectsingleshoebrakedesign2.load = **true, then**
If $\theta > 60^0$ **then**
Enter input parameters: f, N, R, θ ,
Compute the value of torque using equation 3
Beep and note that $\theta > 60^0$
Else if input parameters are: N, R, w, θ
Compute the value of average pressure, using equation 4
End if
End if
If objectdoubleshoebrakedesign.load = **true, then**
If $\theta \le 60^0$ **then**
Enter input parameters: f, N_L, N_R, R ,
Compute the value of torque using equation 6
Else if $\theta > 60^0$ **then**
Enter input parameters: f, N_L, N_R, R, θ ,
Compute the value of torque using equation 7
End if
End if
If objectinternalshoebrakedesign.load = **true, then**
Enter known parameters: $P_m, f, r, a, w, c, \theta_1, \theta_2, \theta_m$,
Compute the value of the force on the right shoe using equation 8
Compute the value of the force on the left shoe using equation 9
Compute the value of torque using equation 15
End if
If objectbandbrakesdesign.load = **true, then**
If it is simple band brake, **then,**
If F_2 is known, **then,**
Enter known parameters: F_2, e= natural logarithm base, f, α,
Compute the value of force using equation 16
Else if F_1 is known, **then,**
Compute the value of force using equation 17
Else if known parameters are: F_1, F_2, r
Compute the value of torque using equation 6
End if
Else if it is a differential band brake, **then,**
Assume a clockwise rotation of drum'
Enter known input parameters: $F_1, F_2, a, b, c, r, w, e$ = natural logarithm base,
Compute the value of force using equation 18
Compute the value of average pressure using equation 19
End if
End if
If objectheatgeneratedratedesign.load = **true, then,**
If known input parameters are: P_{av}, A_c, f, V ,
Compute the value of heat generated rate using equation 20
Else if known parameters are E_k, E_p,
Compute the value of heat generated rate using equation 21
Else if known parameters are: C, Δt , A_r
Compute the value of heat generated rate using equation 22
End if
End if

IX NUMERICAL EXAMPLES

To test the efficiency, accuracy and robustness of the software, the following benchmark problems were solved using the software.

EXAMPLE 1

In a given single shoe brake, calculate the force needed to bring the drum to a stop when the normal force is $2083N$, a is $0.36m$, b is $0.9m$, c is $0.04m$, c is $0.04m$, coefficient of friction is restricted to be 0.35 and the weight of the brake drum is negligible.

Solution

On entering the known parameters, the software produced the following results shown in Fig 4.

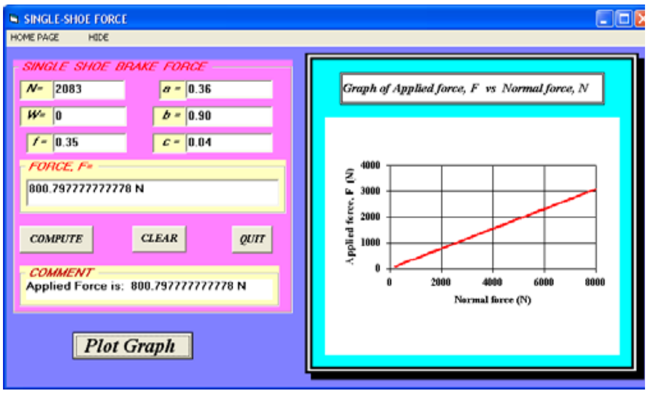

Fig. 4: Output screen of example 1

EXAMPLE 2

In a double shoe brake, the normal force on the left and the right shoes of a double shoe brake are respectively given as $1310\ N$ and $1124\ N$. For the given shoe brake, the coefficient of friction is 0.24 and the internal radius of the drum is 0.9m. Compute the associated torque

.

Solution

On entering the specified input parameters, the result was generated as shown in Fig. 5

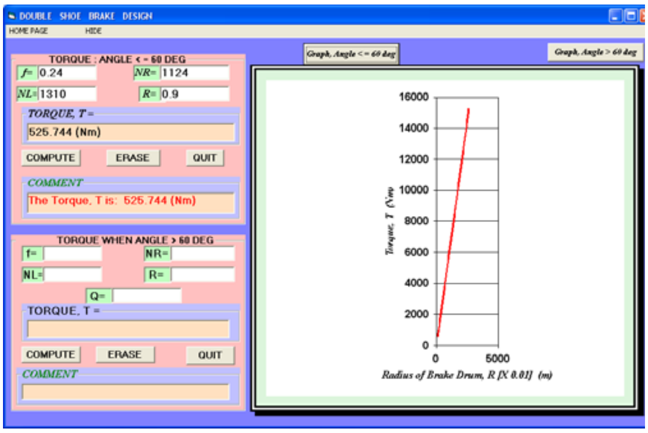

Fig. 5: Output screen for example 2

EXAMPLE 3

In a differential band brake, the force on the tight side of the band is restricted to be 370N. The internal radius of the drum is $0.16m$. The angle of wrap is 180^0 coefficient of friction $= 0.35$, $a = 0.25m$, $b = 0.825m$ and $c = 0.185m$. Compute the applied force and the generated torque in the brake.

Solution

On supplying the specified input parameters, the result was generated as shown in Fig. 6 and Fig.7.

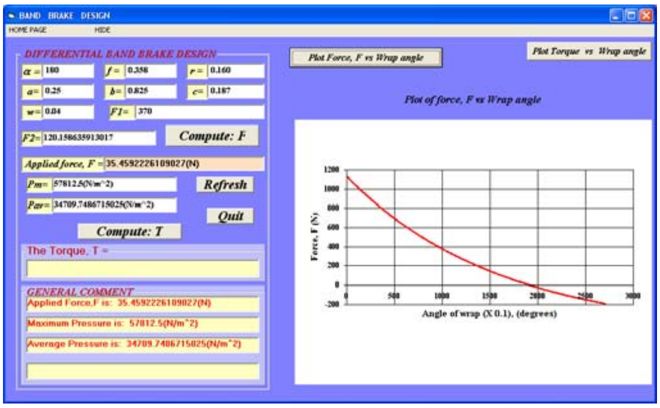

Fig. 6: Output screen for the plot of Applied Force against Angle of wrap in Example 3.

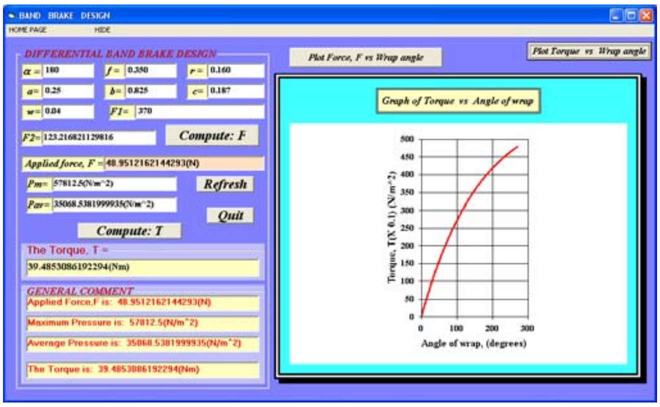

Fig. 7: Output screen for the Plot of Torque vs. Angle of wrap in Example 3

EXAMPLE 4

In a given internal shoe brake, the following parameters were measured: face width of shoe, w = 60mm, coefficient of friction, f = 0.24, maximum pressure in the right shoe $P_m = 1.35MN/m2, a = 125mm$, c=225mm, θ_1=20^0, θ_2=135^0 and the radius of the internal drum, $r = 175mm$.

Solution

On loading the above parameters in the program software, the following results were produced as output this is shown in Fig. 8

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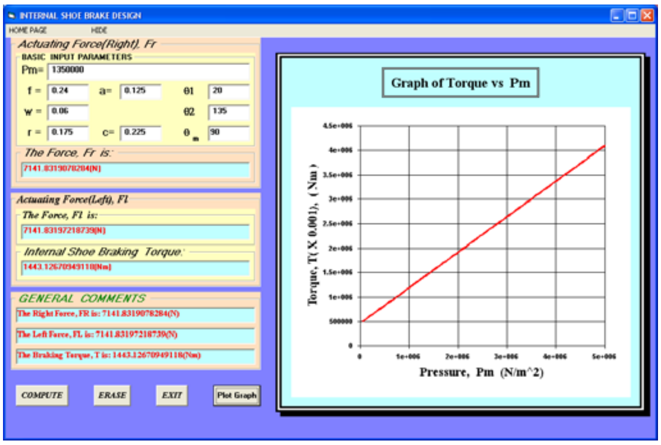

Fig. 8: Output screen for Example 4

EXAMPLE 5

For an experiment carried out on a particular brake, the average working pressure was found to be $1.00MN/m^2$, the contact area is $2.4cm^2$, the coefficient of friction is 0.25 and the associated linear velocity, $V = 4.325m/s$. Calculate the power dissipated as heat i.e. (the heat generated rate).

Solution

On loading the above parameters in the programmed software, the following result (fig. 9) was produced as output.

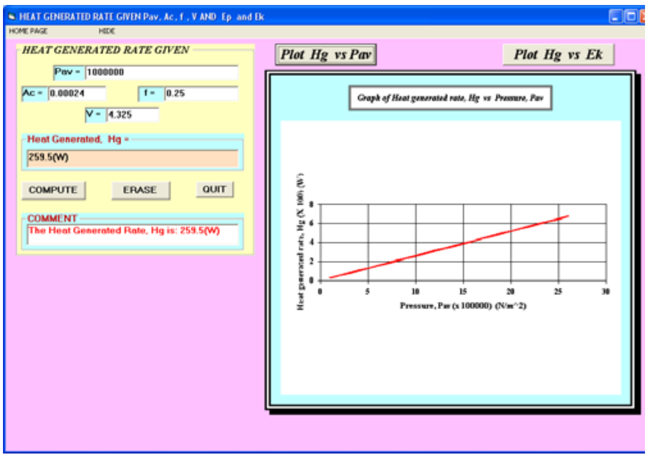

Fig. 9: Output screen for Example 5

EXAMPLE 6

In a given brake, the potential energy rate was given as $E_p = 254.34W$ and the kinetic energy rate was given as $E_K = 675.23W$. Calculate the rate of heat generated by the brake.

Solution

On entering the known parameters, the software produced the following results as shown in Fig.10.

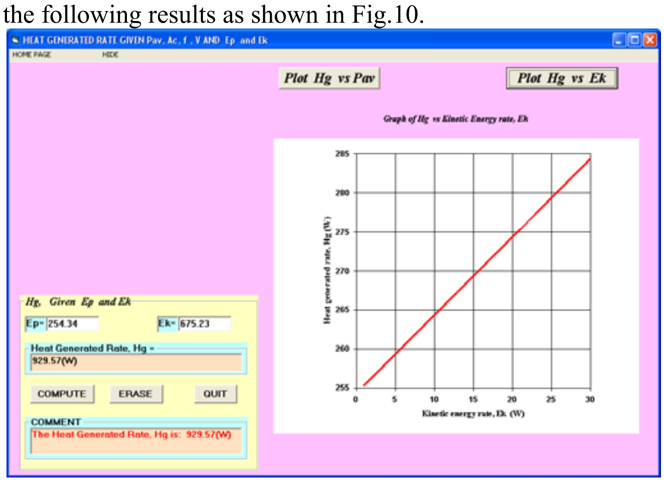

Fig. 10 : Output screen for Example 6.

X DISCUSSION OF RESULTS

The software was tested on a wide range of standard design problems. The results are shown in Figs. 1-10. The numerical results displayed on these figures are highly accurate. The graphs produced for these problems have the following characteristic: Fig. 4 shows that the applied force has a direct and linear relationship with the normal force. Fig. 5 shows that as the radius of the drum of the brake increases, the torque increases proportionately. In all the examples, the software solutions are very accuracy. This is indicated clearly in Table 1.

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Table 1: Software and Manual Results Comparison

S/N	Problem parameter	Computer Generated values	Manually computed values
Question 1	Applied Force (N)	800.79777777778 N	800.797778 N
Question 2	Torque (Nm)	525.744 Nm	525.744 Nm
Question 3	Slack side Force (N)	120.158 N	123.20 N
	Applied force (N)	35.459 N	49.40 N
	Minimal Pressure (N/m)	57812.5 N/m	57812.5 N/m
	Average Pressure (N/m)	34709.7486 N/m	35068.32 N/m
	Torque (Nm)	39.4853086192294 Nm	39.488 Nm
Question 5	Power dissipated as heat	259.50 KW	259.50 KW
Question 6	Rate of heat generated	929.57 KW	929.57 KW

Fig. 6 shows that the relationship between the applied force and the angle of wrap of the band of the brake around the brake drum is an inverse curvilinear. Fig. 7 shows that the relationship between the torque and the angle of wrap of the band of the brake around the brake drum is a direct curvilinear. In Fig. 8 as the maximum pressure in the right shoe of the brake increases, the torque generated increases as well, albeit linearly

In Fig. 9 the rate of heat generation displays a direct linear relationship when plotted against the average pressure on the brake. Fig. 10 shows that the rate of heat generation in the brake varies directly and linearly with the rate of kinetic energy dissipation. Table 1 show the comparison between the solution obtained using the developed software and the solution obtained manually. The results are in close agreement.

A Accuracy and Efficiency

To achieve a high precision always for the solutions, we follow the principles adopted in [11]. First we set the design parameters as double precision. This enabled the accuracy of the solutions to be set at 12 decimal places. We eliminated round off errors by using the computation results as obtained in the set 12 decimal format. To enhance the efficiency of the software we incorporated:

1. Highly efficient time management modules
2. Highly efficient memory usage modules

Speed was test for by embedding the complete code for the software in a loop that was made to continue for one hundred times. The program was then executed on a computer with AMD Turion™ 64x2 mobile Technology TL 58 duo core processors with a clock 2GHz and 2MB DDR Ram. When it was executed on this computer it took 28 seconds to provide the solution. This is considerable improvement in speed as compared to manual design approach (about 45 minutes). The efficient memory usage modules contributed to the very fast processing of the solution. The program was designed such that objects and variables gave up the memory space they occupied at the completion of their assigned tasks.

B Visual Interpretation of Solutions

Graphical features were incorporated in the software to enhance the presentation of the solutions and the ability to speedily and accurately interpret them. Also the graphical solution presents the solution to the specific problem and also extends it. It does this by providing new solutions when a particular parameter is varied (in the design process) while the remaining parameters are held constant. This feature greatly facilitates the teaching of brake design.

C Program Robustness

As stated in [11], a major limitation of commercially available software for machine design is “they provide solutions in a fixed manner”. This is illustrated as follows: A parameter is considered unknown and consequently to be designed for. However when the solution to that design problem is now considered as an unknown parameter and the previously known parameters are treated as unknown, they cannot provide solutions. This problem is easily resolved using the software developed and reported in this work. Thus with this feature we conclude that the developed software is robust to variations in design parameters.

XI CONCLUSION

In this work, computer-aided-design software was developed for brakes. The developed software is basically user-friendly as well as being interactive such that feedback is reported when a wrong entry is entered. Many formulated practical problems have been tested by the software and the results obtained tend to suggest that the software is robust and it also validates the authenticity and accuracy of the software

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