AMERICAN CONSULTING ENGINEERS COUNCIL'S

AFFILIATE

HEAVY MOVABLE STRUCTURES, INC.

4TH BIENNIAL SYMPOSIUM

NOVEMBER 10TH - 12TH, 1992

SHERATON DESIGN CENTER
FT. LAUDERDALE, FLORIDA

SESSION
WORKSHOP NOTES

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"Design/Analysis of Mechanism
....Using Math-Solver Software"

Design and Analysis of Mechanisms on Movable Bridges
Using Math-solver Software

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ABSTRACT

This paper will present the use of a typical math-solver software package to design new mechanisms or to analyze existing mechanisms on movable bridges. The software is based on a programming language similar to BASIC, but different in that equations are written as rules, in any order, and then solved by the iteration method.

This software has been used to design/analyze various types of mechanisms, including end wedges, center wedges, span locks, and other miscellaneous linkages. By using the software, and writing the rules (equations) for the linkage geometry, it is possible to solve for critical maximum force (stress) positions, then size the components accordingly.

As a typical application, this paper will present the design of an end wedge mechanism for an existing swing span, to be the replacement for an existing semi-operational power screw actuated end lift. The end wedge design was later superseded by a new roller end lift design. The program *TK Solver* was used as the math-solver.

INTRODUCTION

The design and analysis of mechanisms for movable bridges can be a tedious and time consuming process. This is especially the case if the process involves "long-hand" calculations in the attempt to optimize the mechanism for minimal forces in the links and actuator.

The obvious solution to this is to write a computer program to solve your problem. The author has written many BASIC programs to solve a variety of design problems, however, the process of writing the programs is again very time consuming. Also, BASIC programming (or even QBASIC) is restrictive in that the equations written must be executed one after the other and the equations have to follow strict rules (eg.: A=B+C/D^2) with the variable to be solved to the left of the equal sign and every thing to the right of the equal sign having known values. (Or zero is assumed! This is a common error in BASIC.)

One alternative to BASIC programs, canned or written, is the use of a software package known as TK Solver. TK Solver is a declarative, rule-based programming language which lets you work directly with the mathematical description of your problem (rules) without the restriction of placing the equations in the proper order for solution or always placing the unknown quantity on the left side of the equal sign (eg.: B+C/D^2=A is permissible). The program has both a DIRECT SOLVER and an ITERATIVE SOLVER. This allows for the solution of simultaneous equations with many unknowns without the need of setting up a sequential solution procedure.

INTRODUCTION TO TK SOLVER

The author was first introduced to TK Solver via a promotional demo disk which allowed the user to actually see some of the elementary features by writing equations (rules) and letting TK find the unknowns by iteration or direct solution. For someone with BASIC programming knowledge, it is an easy step to writing rules in TK.

There are many similarities between TK and BASIC; for instance the mathematical operators are the same as in BASIC: +,-,/,*,^ for plus, minus, divide, multiply, and exponential.

The built-in trig functions are the same but with the addition of many others (regular and hyperbolic), and the choice of having radians or degrees for the arguments. For example: SIN(X) for angle X in radians or SIND(X) for angle X in degrees; COS(X) or COSD(X); ASIN(X) or ASIND(X); etc.

The logarithmic functions include not only the natural logarithms [LN(X)] but also logarithms to the base 10 [LOG(X)]. Also the numeric values of PI [PI()] and the natural log base e [E()] are built-in; no need to define them.

Logical expressions are the same as with BASIC, the most commonly used being the IF THEN ELSE statement and the operators: >=, <=, >, <, =, <> for greater than or equal to, less than or equal to, greater than, less than, equal to, and not equal to respectively. (Example: IF X<=Y THEN X=Y ELSE X=0.)

But the differences are what makes TK SOLVER a valuable computer aided design tool. Upon initiating TK Solver, you are presented with a split screen, two windows, the upper one is the Variable Sheet and the lower one is the Rule Sheet. (See Figure 1.) The Rule sheet is the active window, meaning you can immediately start entering Rules. After typing in a Rule, press RETURN then the down arrow (↓) to get to the next line. (Only pressing RETURN, you will over-type the previous Rule, deleting it!) As the Rules are entered, the variable names appear on the Variable Sheet.

```
(1r) Rule:
For Help, type ? or press F1
=================== VARIABLE SHEET ================================
St Input---- Name--- Output--- Unit----- Comment--------------------




==================== RULE SHEET ====================================
S Rule--------------------------------------------------------------




 F1 Help  F2 Cancel  F5 Edit  F9 Solve  / Commands  = Sheets  ; Window
```

Figure 1. Split Window Screen of TK Solver

To run a program, it is necessary to give the known input values on the Variable Sheet, *INPUT column*. Pressing the semi-colon (;) switches the active window to the other sheet. For a set of simultaneous equations, it is necessary to assign some guesses to some of the variables so that the ITERATIVE solver can work. In the St (STATUS) column place a G to tell TK that the input value is *not fixed*, but used only as an initial guess.

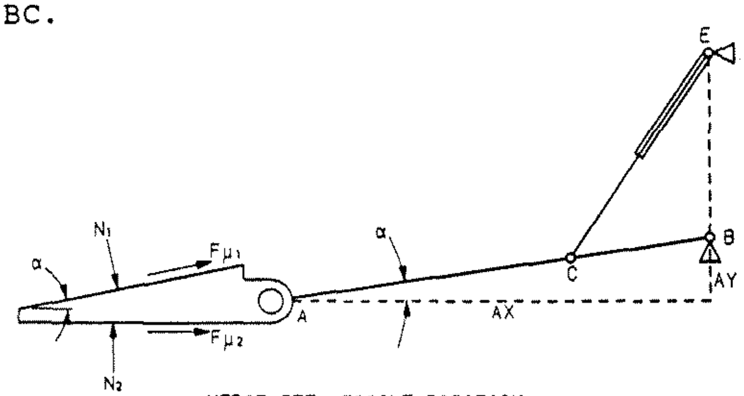
The ITERATIVE solver (or DIRECT solver) is started by pressing function key F9 (a prompt line is at the bottom of the screen). Each successive iterative solution uses an updated guess until the error is small enough to stop or the number of iterations exceeds the preset value (default setting is 10; it can be changed). The final solutions for the variables appear in the OUTPUT column. Unit and Comment columns are also on the Variable sheet for giving the variable units and remarks on the variable names. Comments on the RULE sheet must be placed inside quote marks "_________" and may be part of an arithmetic rule or stated as a separate rule.

One of the special features of TK Solver is that it is possible to LIST solve a set of rules. Typically, one independent variable might control the numeric value of a group of other dependent variables. It is possible to set up a list of numeric values for the independent variable and then LIST SOLVE to find the numeric values of the other variables. Any variable which has a list associated with it is specified as a LIST variable by placing an L in the STATUS column for that variable on the Variable Sheet. After LIST solving, it is possible to present these variables in table form using the TABLE Sheet or to plot any of the variables as a function of the independent variable using the PLOT Sheet and the PLOT routine.

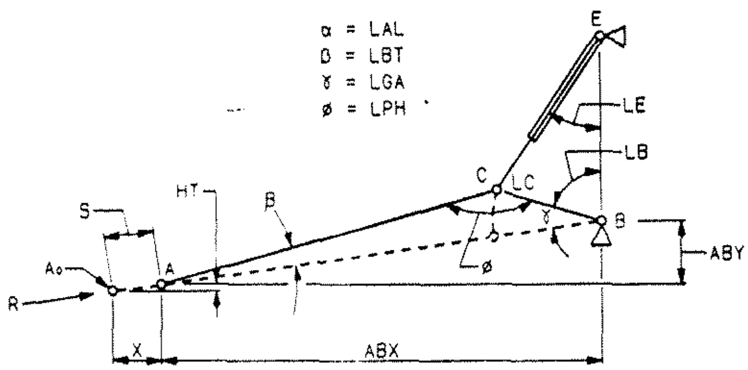
Pressing F7 plots to the screen and from the screen display, pressing O (letter O for Output) dumps the plot to the printer.

DESIGN/ANALYSIS OF AN END WEDGE MECHANISM USING TK SOLVER

Figure 2. shows the model used to determine link geometry and member forces using TK Solver. The original design included an actuator (hydraulic cylinder) attached at C, the joint between links AC and BC.



WEDGE SET, TOGGLE POSITION
(a)



WEDGE, ARBITRARY POSITION
(b)

Figure 2; TK SOLVER Wedge Model

Part (a) of the figure shows the end wedge in the locked-set (toggle) position. It also shows the friction forces $F\mu_1$ and $F\mu_2$. The friction forces would be in the directions shown when setting the wedge and opposite when retracting the wedge. The TK program could be written to account for both sets of forces-forces required to set the wedge, and forces required to retract the wedge, each with different coefficients of friction. The wedge reaction force R would also change direction from that shown in the figure for the retraction of the wedge.

The horizontal distance X (distance of retraction from set position) was chosen as the independent variable. Variable lengths ABX, ABY, AB, and CE (hydraulic cylinder length) and all the angles are a function of X. Once the geometry equations (Rules) are written, the linkage forces can be found for any position. See Figure 3 for the complete listing of the RULES used to find all lengths, angles, and forces.

```
==================== RULE SHEET========================================
S Rule-----------------------------------------------------------------
  "SAVED AS ENWDMBS1.TK"
  "Rules for End Wedge; N2=40 kips(MAX); MU1 & MU2 variable input"
  "GEOMETRY EQUATIONS"
* LAL=ATAND(1.0/6.0)
* ABO=AC+BC
* AX=ABO*COSD(LAL)
* AY=AX*TAND(LAL)
* HT=X/6
* S=SQRT(X^2+HT^2)
* ABY=AY-HT
* ABX=AX-X
* AB=SQRT(ABX^2+ABY^2)
* LBT=ACOSD((AB^2+AC^2-BC^2)/(2*AC*AB))
* LGA=ACOSD((AB^2+BC^2-AC^2)/(2*AB*BC))
* LC=ACOSD((CE^2+BC^2-BE^2)/(2*CE*BC))
* LPH=180-LBT-LGA
* LB=90-LGA+LAL
* LE=180-LB-LC
* CE=SQRT(BC^2+BE^2-2*BC*BE*COSD(LB))
  "FORCE EQUATIONS"
* IF X<=5.95 THEN N2=40000-6666.67*X ELSE N2=0
* N1=N2*COSD(LAL)-MU2*N2*SIND(LAL)
* R=MU1*N1+MU2*N2*COSD(LAL)+N2*SIND(LAL)
* FAC=R/COSD(LBT)
  "GUESS AT ONE OF UNKNOWNS, EITHER FCE OR FBC"
* FAC*COSD(LBT+LAL)=FCE*SIND(LE)+FBC*COSD(LGA-LAL)   "SUM OF F(X)=0"
* FCE*COSD(LE)=FAC*SIND(LBT+LAL)+FBC*SIND(LGA-LAL)   "SUM OF F(Y)=0"
* FCYL=INT(FCE)
* FBCI=INT(FBC)
```

Figure 3. Listing of the RULES Sheet

The bridge reaction force N2 must be known for the set position of the wedge. Also, the deflection of the bridge end must be known, and therefore the amount of retraction (X) to zero N2 force will be known based on the given wedge slope (in our case 1/6). A rule to find N2 as a function of X is the starting point in finding the wedge reaction force R and then the link forces. First FAC was solved, then two simultaneous equations were written to solve for FBC and FCE. The equations represent the equilibrium of Pin C and are for $\sum F_X=0$ and $\sum F_Y=0$. The ITERATIVE Solver is used automatically to solve for the values FBC and FCE.

The first group of Rules is used to define all the general geometry relations. All variable names beginning with L are angles, as labeled in Figure 2(b). The second group of Rules is used to find the forces in the various members.

Figure 4 shows the VARIABLE Sheet. By default, as the Rules are written, the variable names used are automatically placed on the Variable Sheet. It is then necessary to place the fixed variable values in the Input column.

=================== VARIABLE SHEET =================================

St	Input----	Name---	Output---	Unit-----	Comment---------------------
		LAL	9.4623222	DEG.	MOVABLE BRIDGE SYMPOSIUM
	30	AC		IN.	END WEDGE MODEL
	21	BC		IN.	ACTUATOR ATTACHED AT C
	52.5	BE		IN.	
	.18	MU1			MU1=MU2=0.18;
	.18	MU2			CHANGE AS REQUIRED
L	0	X		IN.	
		ABO	51	IN.	
L		S	0	IN.	
L		HT	0	IN.	
L		ABY	8.3843484	IN.	
		AY	8.3843484	IN.	
L		ABX	50.30609	IN.	
		AX	50.30609	IN.	
L		AB	51	IN.	
L		LBT	0	DEG.	
L		LGA	0	DEG.	
L		LPH	180	DEG.	
L		FAC		LBS.	
L		R		LBS.	
L		BCT		IN.	
L		N2	40000	LBS.	
L		N1	38272.084	LBS.	
L		LB	99.462322	DEG.	
L		CE	59.663639	IN.	
L		LC	60.222493	DEG.	
LG	20566.971	FBC		LBS.	ENTER A GUESS FOR FBC OR FCE
LG	0	FCE		LBS.	FOR SIMULTANEOUS EQS SOLUTION
L		LE	20.315184	DEG.	
L		FCYL	0	LBS.	
L		FBCI	20566	LBS.	

Figure 4. The VARIABLE Sheet.

For any variables that you desire to have a LIST output, place an L in the Status column of the Variable Sheet. The status column also contains a G for the variables which require a guess in order for the Iterative Solver function. For LIST solving, it is necessary to go to the variable subsheet and insert the first guess here also. In our case, the Variable FBC subsheet contains the First Guess of 20566. (See Figure 5.)

```
==================== VARIABLE: FBC ====================================
Status:                     LGuess
First Guess:                20566
Associated List:            FBC
Input Value:                20566.9709078494
Output Value:
Numeric Format:
Display Unit:               LBS.
Calculation Unit:           LBS.
Comment:                    ENTER A GUESS FOR FBC OR FCE
```

Figure 5. VARIABLE:FBC Subsheet

The Output column will contain the answers, once the Rules are solved. The Unit and Comment columns are optional, for reference only.

Before LIST solving, it is necessary to define the independent variable values, for the number of elements required.

Each value can be manually placed in the list (in our case LIST:X) or if in a linear sequential order, it is possible to input the first and last value and the number of elements, and the list will be automatically filled. The LIST:X Subsheet is shown in Figure 6. Then to List solve, press function key F10.

After LIST solving, each List variable (for which an L was placed in the Status column of the Variable sheet) will have a list of solved output values. These lists may be placed into a Table of results using the TABLE sheet.

The TABLE sheet is called by typing =T. Give the table a name, title, and list the variables you want in the table. If desired, you can have more than one table of values. The table of values can be modified by specifying the field width for each variable. The width includes the decimal point if required. Also, the Numeric Format may be specified- uniform for all variables by use of a Global Format or different for each variable if desired. The TABLE SHEET and subsheet are in Figure 7, and for our example, Table X output is as shown in Figure 8.

```
==================== LIST: X ========================================
Comment:
Numeric Format:
Display Unit:                IN.
Calculation Unit:            IN.
Element-- Value--------------
1          0
2          .5
3          1
4          1.5
5          1.75
6          2
7          2.25
8          2.5
9          3
10         4
11         5
12         6
13         7
14         8
15         12
16         16
17         20
```

Figure 6. LIST:X Subsheet

```
==================== TABLE SHEET ====================================
Name---------- Title------------------------------------------------
X              "ENWDMBS1.TK" END WEDGE-  MU1=MU2=0.18; N2=40 KIPS(MAX)
```

(SUBSHEET: >)

```
==================== TABLE: X ========================================
Screen or Printer:         Screen
Title:                     "ENWDMBS1.TK" END WEDGE-  MU1=MU2=0.18; N2=40
Vertical or Horizontal:    Vertical
Row Separator:
Column Separator:
First Element:              1
Last Element:               21
List----- Numeric Format-- Width-- Heading---------------------------
X                          5
R                          5
                           3
LBT                        3
LPH                        3
LC                         3
LE                         3
                           3
FAC                        5
FBCI                       5
CE                         5
                           3
FCYL                       5
```

Figure 7. TABLE SHEET and TABLE X subsheet.

```
=================== TABLE: X=========================================
Title:       "ENWDMBS1.TK" END WEDGE-  MU1=MU2=0.18; N2=40 KIPS(MAX)
Element X---- R---- --- LBT LPH LC- LE- --- FAC-- FBCI- CE--- --- FCYL-
1       0     20567     0   180 60  20      20567 20566 59.66      0
2       .5    18853     6.8 164 68  22      18985 16081 56.47      5775
3       1     17139     9.5 157 72  22      17380 13724 55.08      7219
4       1.5   15425     12  151 75  23      15752 11780 53.99      7796
5       1.75  14568     13  149 76  23      14929 10901 53.5       7883
6       2     13711     13  147 77  23      14100 10069 53.05      7869
7       2.25  12854     14  145 78  23      13266 9276  52.62      7768
8       2.5   11997     15  143 79  23      12425 8517  52.21      7590
9       3     10283     16  140 81  23      10725 7085  51.44      7039
10      4     6856      19  133 85  23      7252  4486  50.05      5306
11      5     3428      21  128 88  24      3678  2148  48.8       2915
12      6     0         23  122 91  24      0     0     47.66      0
13      7     0         25  118 94  24      0     0     46.59      0
14      8     0         27  113 97  23      0     0     45.58      0
15      12    0         32  98  108 22      0     0     42.01      0
16      16    0         37  84  119 20      0     0     38.96      0
17      20    0         40  72  131 18      0     0     36.3       0
```

Figure 8. TABLE X Output Results

To get a graphical representation of the results, it is possible to plot any of the output. Go to the PLOT Sheet by typing =P and give the plot a name, then plot type, display, output device and title. Use the plot subsheet to list the X and Y variables and other information as asked for. See Figure 9 for the PLOT Sheet and LINE CHART subsheet.

```
=================== PLOT SHEET ====================================
Name--------- Plot Type-- Display Option- Output Device- Title--------
enwl          Line chart  1.VGA                          FORCES IN
                                                            ACTUATOR
```

(SUBSHEET: >)

```
=================== LINE CHART: enwl ===============================
Display Scale:                Yes
Display Zero Axes:            None
Display Grid:                 Yes
Line Chart Scaling:           Linear
Title:                        FORCES IN ACTUATOR CYL CE VS. X
X-Axis Label:                 DISTANCE, X (INCH)
Y-Axis Label:                  FCYL  LBS
X-Axis Minimum, Maximum:      0,7
Y-Axis Minimum, Maximum:
X-Axis List:                  X
Y-Axis--- Style------ Character-- Symbol Count-- First-- Last---
FCYL      Lines                   1              1
```

Figure 9. PLOT SHEET and LINE CHART Subsheet

Once all the information is completed, pressing F7 will place the plot on the screen. While on the screen, the plot can be dumped to the printer by pressing the letter O. See Figure 10 for the plot of cylinder force FCYL as a function of the distance retracted X. It is possible to plot several variables versus the independent variable X if desired. Each can be given a separate character so that the curves are defined.

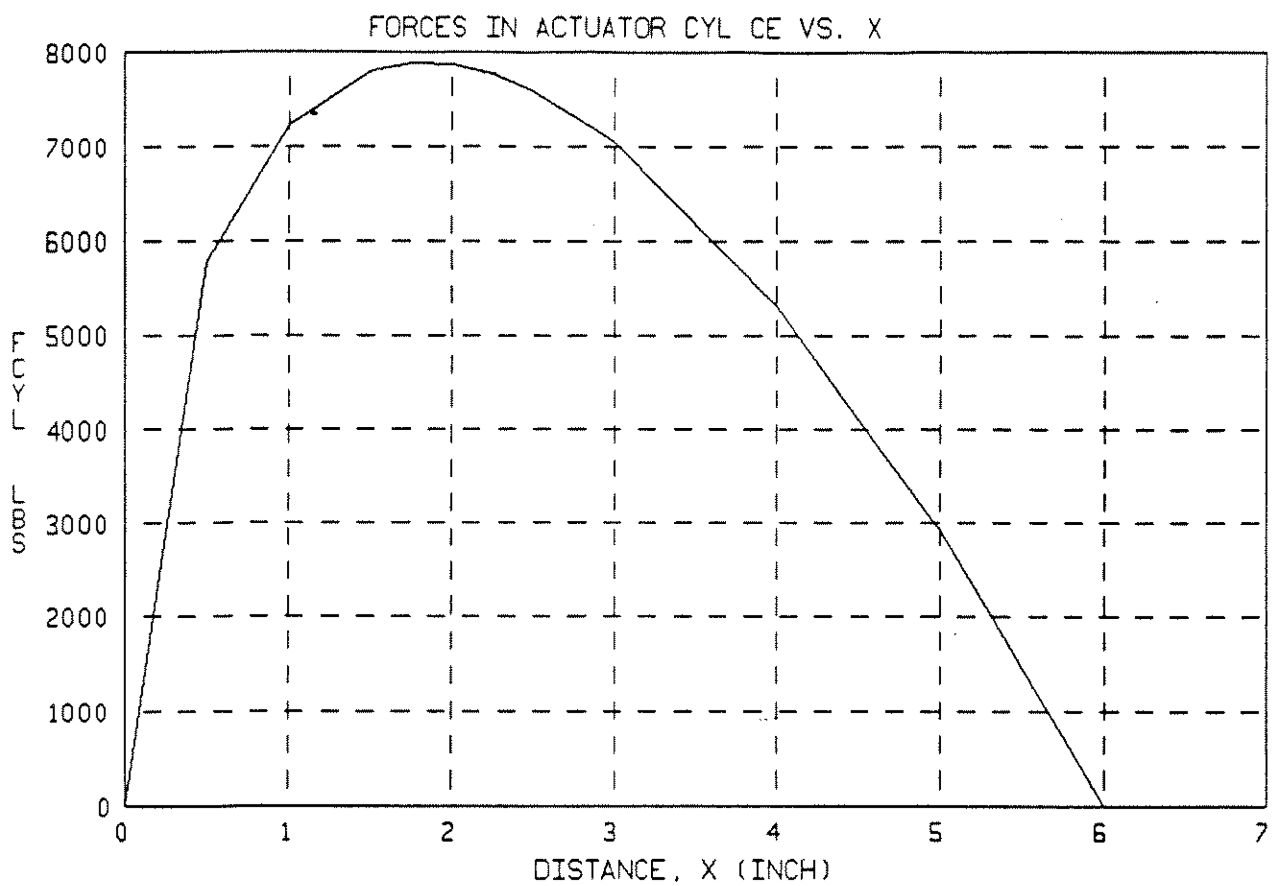


Figure 10. Plot of Cylinder Force vs. Distance X

SUMMARY

The purpose of this paper was to present a method for the design or analysis of mechanisms on movable bridges, using the purchased software program TK SOLVER Plus.

The use of TK Solver for the preliminary design of mechanisms can be a valuable computer tool in optimizing the design for most efficient use of materials and components. Once the RULES are written for the general geometry of the mechanism, they can be used for different input criteria- lengths, angles, and forces. Also, the Iterative Solver is useful for the solution to simultaneous equations, which can prove to be an advantage over BASIC programming and matrix methods.

REFERENCES

Introduction and Reference Manuals, TK Solver Plus; Universal Technical Systems, Inc., Rockford, Illinois, 1989