Numerical Methods on Spreadsheet for Machinery Design Projects*

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This paper describes an experience on assigning two semester-long computation-intensive design projects to a mechanisms class. Each assignment required the students to work through a series of Tasks over the entire semester. In one assignment, each group designed a mechanism which would de-water a moored small boat in rain and is powered by the rocking motion of the boat. In the other assignment, each group designed a piston-crank linkage and a cam-follower in a valve train for a small internal combustion engine. Most computations, including using various numerical methods, were carried out on a spreadsheet.

INTRODUCTION

TEACHING the engineering subjects today can be a challenge when one attempts to keep pace with the rapidly evolving computer hardware and software. Teaching the subject of mechanisms is no exception. To teach mechanisms in one semester in Spring 1995 for a class of 20 mechanical engineering juniors, the author felt that the class could best learn the subject by working on some design project(s) progressively from beginning to the end of the semester, while solving the numerous small and discrete problems from the textbook could be left to the students' self-managed studies. The author thus decided on and gave to the class the two design assignments described and discussed in this paper. More discussions on integrated approach on homework assignments can be found in Reference [1].

The two projects were chosen to provide a balanced coverage of the two important types of mechanisms: the four-bar linkage and the slider-crank linkage. Each project was given to the class in a series of Tasks with each Task requiring the students to apply a certain topic or topics just covered in lectures.

The class was broken into 10 two-member design teams and all teams complete each Task once a week in a CAD lab for a continuous two and half hours in a workshop format. Each team used one Macintosh Quadra 650 or Macintosh IIci and all shared one laser printer. Microsoft *Excel* for spreadsheets and graphing, and Microsoft *Word* for report preparations were the two primary utility software used. *Cricket Graph* and *Engineering Equation Solver* were available for use at the students' discretion. *Working Model* and *Lincages* were the two application software used for verification at various stages of their design. Graphical analyses were also used for spot check

whenever possible. All formulas used were either directly taken from the text of Norton [2] or with modifications by the author before giving them to the class. Since the primary purpose of this paper is to examine the use of spreadsheets, aspects that are not directly relevant to this purpose are mentioned for completeness only. Figures presented in this paper are not to scale.

To limit the size of this paper, the author assumes that the reader is familiar with typical spreadsheet operations and therefore examples of spreadsheet screens are intentionally not included in this paper.

PROJECT DRYBOAT

The blueprints of an actual 6.34-meter (24-foot) sailboat used for training at the US Coastguard Academy were given to the class. For this boat, when moored in rain, a de-watering machine is to be designed. A 4.4-cm (2-inch) diameter, 13.2-cm (6-inch) stroke hand pump was purchased and placed in the lab and was to be installed and driven by the linkage. The pump was to be either fixed or hinged to the bottom of the boat's pit.

Many different concepts were created graphically and cardboard models were constructed in their *first Task* (the first lab period in the semester). The second Task, the analytical position analyses, reduced the linkage concepts among all the teams to three basic categories, namely, pump fixed, pump pivoting, and the Watt's straight-line linkage which was suggested by the author. The Watt's straight-line linkage was suggested by the instructor intentionally for inclusion of a precision point P (see Fig. 1) on the coupler link AB in their analytical position analyses. The Watt's straight-line linkage entailed an analytical three-position synthesis requiring three precision point positions on a vertical straight line. The analytical linkage synthesis was completed in a

spreadsheet by inverting the three-position coefficient matrix. The resulted linkages were subsequently modeled and animated using the *Lincages* software for verification of the coupler curve, transmission angles, and toggle positions.

The subsequent translational and rotational velocity analyses, Task #3, were based on the assumption that the 'rocking' or 'rolling' motion of the boat can be described by a simple sine function with a 10° single amplitude and a natural period τ of 10 s. For convenience, the boat was treated as the ground link (link 1) for all the kinematic and force analyses of the linkage. Thus the rocking motion of the boat is represented by the rotational motion of the coupler link in all analyses. Corrections were not made in solutions for the fact that the boat is actually rolling instead of the coupler. Thus the force analysis was strictly an academic exercise and should not be used for any subsequent strength design if it were to be carried out. This point was made clear to the class.

Translational and rotational accelerations at the centers of gravity of all the links as well as at the precision point were then determined in Task #4. All links were assumed to be made of 4.4-cm (2-inch) diameter schedule 40 aluminum pipes. This assumption was made to facilitate the determinations of center-of-gravity locations, mass, and mass moment of inertia of all the links. These dynamic properties were then entered in the equations of motion.

In the force analysis, a load for operating the pump was applied to the linkage at the precision point on the coupler. Inversion of coefficient matrix of simultaneous equations of motion were then carried out on a spreadsheet in Task #5. The results were the solutions of all the unknown forces at all the hinged joints including the support joints and the 'reaction' torque about the center of gravity of the coupler. This reaction torque represents the input torque to be supplied by the floats on the water surface on both sides of the boat. Knowing the internal forces at the joints during one complete roll period, all the links and their hinged connections can be checked for their strength integrity. The strength design was not included in the project as it is outside the scope of a typical mechanisms course. (This point was
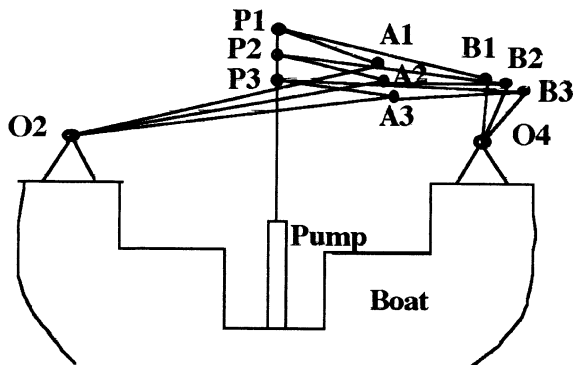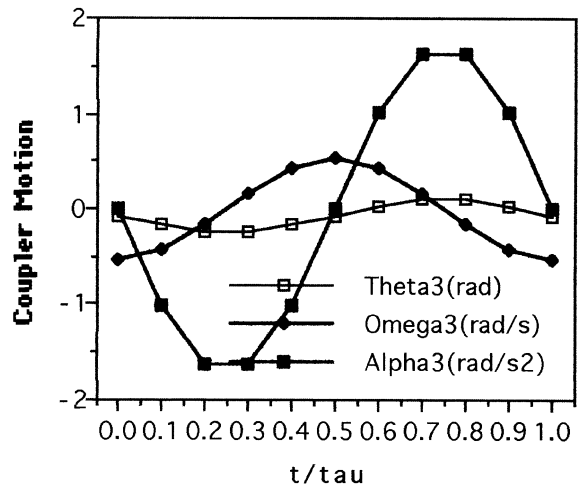
made clear to the class for their connections to the course Machine Design.)

Each Task repeated its analysis at ten equal time intervals covering one natural period of the boat's rolling motion. Thus a complete numerical 'simulation' of the linkage in operation can be presented by plotting the eleven data points generated. Figure 2 gives one such plot for the coupler link (link 3, from A to B in Fig. 1) only. The angular motion of link 3 is described in Fig. 2 by the three curves which represent position θ, velocity ω, and acceleration α of the link. The angle is measured from line O2–O4 to line A–B.

In the solution of the simultaneous equations of motion, an external 'reaction' torque was applied at the center of gravity of the coupler link and was treated as an unknown reaction. Figure 3 is a plot of this driving torque in one cycle of the boat's rolling motion. Knowing that knowledge of this driving torque is needed for the design of the floats, the design was not required on the part of the students.
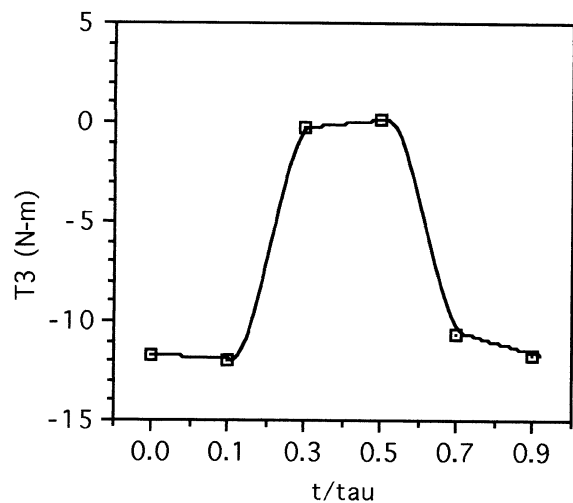

Fig. 2. Coupler kinematics.

Fig. 1. Watt's straight-line linkage for de-watering the boat.

Fig. 3. Driving torque on coupler.
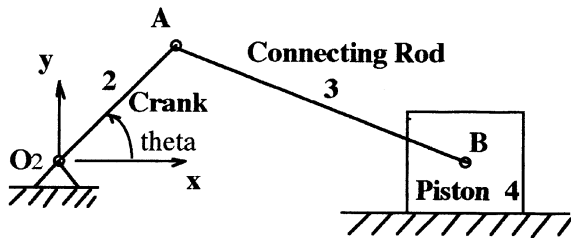
Fig. 4. The piston-crank linkage.

PROJECT ENGINE

The slider-crank linkage design for a 4-stroke internal combustion engine was assigned to the class with a required piston displacement given to each team. A 230 cm³ (21.58 cubic inch) displacement per cylinder, 4-stroke internal combustion engine with an opposite-two cylinder configuration was disassembled and placed in the lab serving as a point of departure for their own design.

A piston-crank linkage was first synthesized graphically in Task #1 with due considerations of piston displacement, bore-to-stroke ratio, and conrod-to-crank ratio (Fig. 4).

The subsequent analytical position, velocity and acceleration analyses (Tasks #2, 3 and 4) were carried out on the spreadsheet in 9° increments for one complete 360° crank revolution and at the constant crank rotational speeds from 500 to 3000 rpm in 500-rpm increments. These analyses were relatively straight forward and the results for engine running at 2000 rpm only are given in Figs 5, 6 and 7. In Fig. 6, F12xc and F12yc represent the x and y components of the shake force at the mainpin (crank shaft) after the shake forces by the two opposing cylinders are combined.

The force analysis in Task #5 was in essence an undamped multi-rigid-body dynamic analysis of the piston-crank linkage operating at a constant crank rotational speed. The eight simultaneous equations of motion of the piston, connecting rod, and crank were solved by inverting the coefficient matrix on the spreadsheet and the solutions
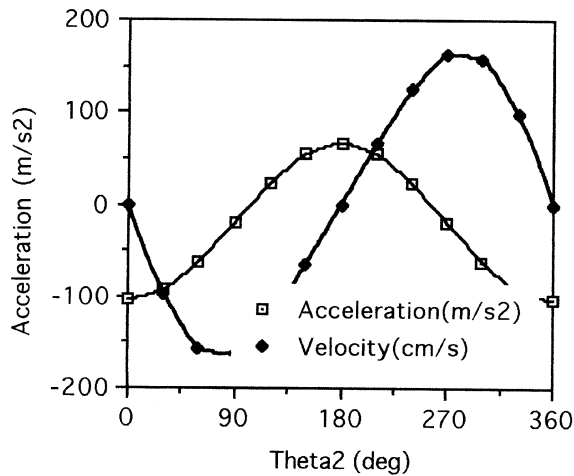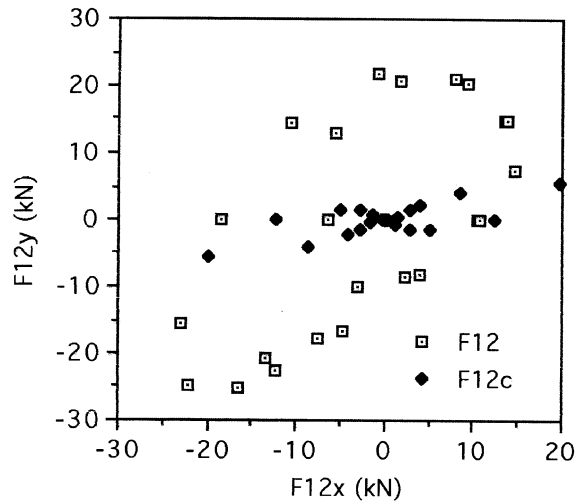

Fig. 6. The shake force at the mainpin.

were the internal forces at the wrist pin and crank pin and the reactions (two forces and a torque) at the mainpin and between the piston and the cylinder wall (normal). No friction was included for simplicity.

The shake forces and the torque fluctuations at the mainpin are given in Figs 6 and 7. In Fig. 6, plotting the y-component of the shake force against its own x-component is one way of describing the history of shake force during one engine revolution at the mainpin (crank bearing). The origin of the plot is the location of the bearing and each data point is the tip of the shake force vector.

In Fig. 7, The torque at the mainpin due to one cylinder, the combined torque due to the two opposing cylinders, and the resulting average torque, all at the idling crank speed of 500 rpm were plotted against the engine crank angle for one engine revolution. The two-cylinder combined (superposed) torque and the average torque were then used for sizing the flywheel (task #6). A simple numerical integration was performed on
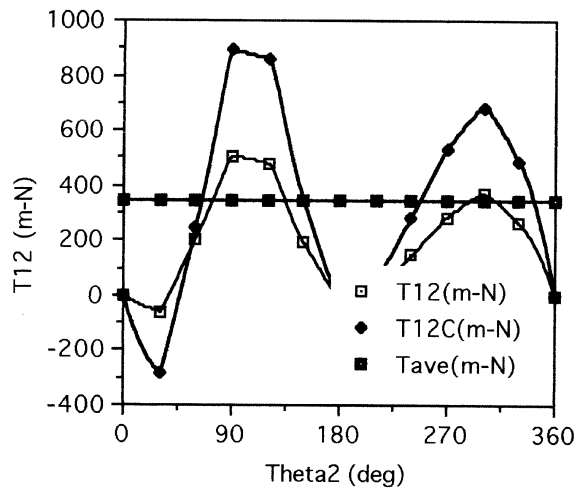

Fig. 5. Piston kinematics.

Fig. 7. Output torque fluctuations.

spreadsheet and the required moment of inertia of the flywheel was calculated which would give a coefficient of fluctuation of 0.05.

While the shake force is seen to have been attenuated by the two opposing cylinders, the torque fluctuations as seen in Fig. 7 are additive. An area integration under the combined torque curve for the case when the engine is idling at 500 rpm (the torque curve of which is not shown here) was then carried out and used for sizing the flywheel.

Finally, Task #7 concluded the engine design project by designing a cam lobe for generating a flat-faced follower motion for operating the intake or exhaust valve. A sixth-degree polynomial function was chosen for the description of the desired follower motion. A double harmonic description was also used for comparisons. The double harmonic description, in terms of its resulted follower motion, was judged less favorably and was rejected. The follower motion program for operating the intake (and same for the exhaust valve with a certain phase shift) were scheduled for a 55° rise, a 55° fall, and a 250° dwell for each complete revolution of the cam.

The seven unknown coefficients for the sixth-degree polynomial were determined by solving the seven simultaneous equations of seven boundary conditions. These boundary conditions are the statements of zero displacement, velocity, and acceleration at the beginning and end of the rise-fall duration and the total lift at the rise-to-fall transition. Once these unknown coefficients were solved on the spreadsheet, successive derivatives of the polynomial gave the complete displacement s, velocity v, acceleration a, and jerk j during each revolution of the cam. Figures 8, 9 and 10 are the results of one student's work. It can be seen in Figs 8 and 9 that the follower motion satisfy the requirements that the jerk j is 'finite' all the time. Once the follower motion was judged acceptable, the cam profile, as described by the r and q values at each of all the cam angles were then
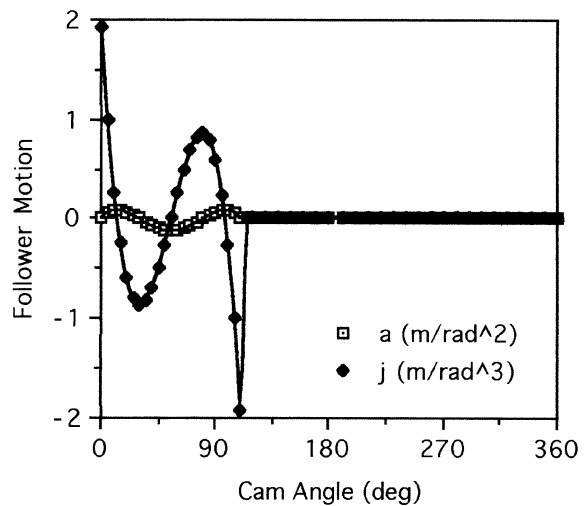

Fig. 9. Cam follower acceleration and jerk.

calculated on the same spreadsheet and plotted (see Fig. 10).

DISCUSSION AND CONCLUSION

The spreadsheet software Microsoft *Excel 4.0* on Macintosh Quadra 650 and IIci was found adequate and convenient for all computational and plotting needs of the two projects. The use of a spreadsheet made possible the completion of all the extensive computations in the design and analyses in both projects in one-semester time frame. The ability of plotting simultaneously on the screen by *Excel* while performing spreadsheet work made it particularly convenient for result validation at various stages of computation.

Because of the computational feasibility offered by the spreadsheet, the students gained much deeper understanding and intimacy of the subject on mechanisms during the two project experiences. Application software such as *Working Model* and *Lincages,* as well as the software that came with the text by Norton (2), served well
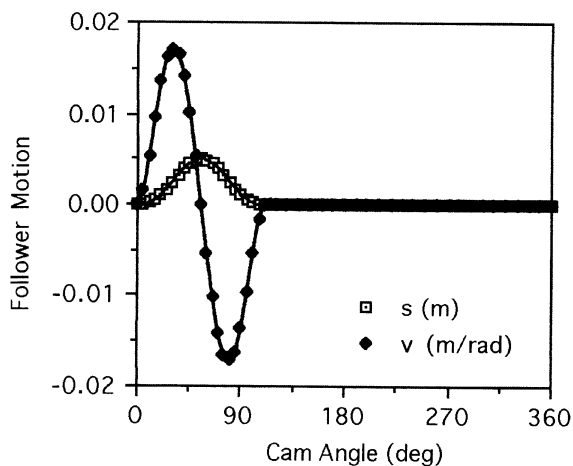

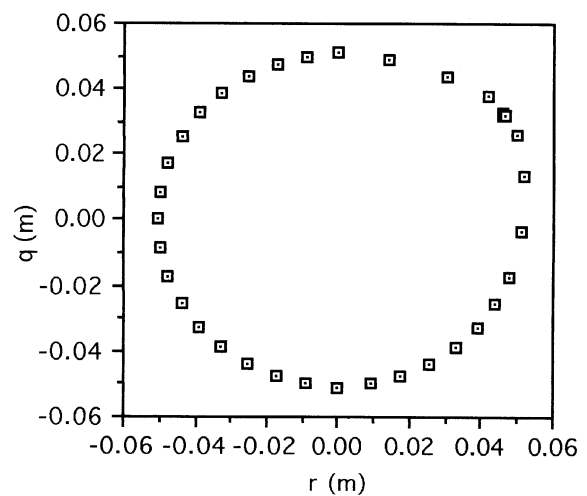Fig. 8. Cam follower displacement and velocity.

Fig. 10. Cam profile.

as 'solution manuals' or 'answer keys' for validating students' results at various stages including the validation of their initial conceptualization and their final 'products'. With today's powerful computer software and hardware, the students found the position simulation by a cardboard model in their early conceptualization stage of design still indispensable.

REFERENCES

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2. R. L. Norton, *Design of Machinery,* McGraw-Hill, Inc. (1993).

Paul K. Yin was born in Weihaiwei, Shantung, China. He graduated from the National Taiwan University with a bachelor degree in agricultural engineering. He then studied at the Texas A&M University and graduated with a master's and a doctor's degree both in mechanical engineering. Following the completion of his graduate studies he worked for 11 years with Brown and Root, Inc. and other engineering consulting firms on designing industrial process equipment and then on offshore structures. It was then followed by another 12 years of teaching marine and mechanical engineering with the Texas A&M University at Galveston as an assistant professor and the United State Coastguard Academy as an associate professor. He is now working as a senior structural engineer with Le Turneau, Inc. on designing the mobile offshore drilling units.