Incorporating Optimization in the Study of Rocket Propulsion
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Abstract

This paper describes the integration of genetic algorithm based design optimization into the rocket propulsion course at Auburn University. Some background on the course is included. This is followed by a discussion of the motivation for design optimization, the mechanics of the optimization tools introduced into the course and the student response to the optimization component of the course.

Introduction

The Aerospace Engineering Department has offered courses in the study of Rocket Propulsion and has conducted research in this area for more than thirty years. Throughout this period, the course work has focused on the fundamental principles of liquid rocket engines and solid rocket motors. Design has always been a part of this fundamental material but in the past, design optimization has not been within the practical scope of the course material primarily because the methods available were not temporally compact enough to include. However, over the past decade, design many types of optimization tools have become much more efficient and user friendly. Indeed, optimization of design is now taught in many senior level undergraduate design curriculums for a range of disciplines. Recent research efforts at Auburn have focused on design optimization of rocket motors, rocket engines and the missiles that they power. The primary tool employed in this effort is a genetic algorithm (GA). The most recent research efforts have included the implementation of a graphical user interface (GUI) for the GA derived optimization tool for missiles. With the inclusion of the GUI, the GA driven optimization tool became compact enough to include in some limited forms in the course material. During the spring of 2006, this optimization work was introduced and incorporated in the design content of the advanced undergraduate/graduate course in rocket propulsion referred to as AERO 6520.

Coursework Description

The rocket propulsion course in the AE department at Auburn covers the basics of both solid rocket motor propulsion and liquid rocket engine propulsion using Sutton’s text as the basic resource and many other texts and papers as reference material. The major topic areas covered in the course include: fundamentals of chemical rocket propulsion, generic thermodynamics and gas dynamics of chemical rockets, liquid rocket engine components/systems liquid rocket propellants and combustion, thrust-time curves for solid motors propellant burning in solid motors, transient performance in solid
motors, geometry of grain design, internal ballistics, and now optimization of motor
design. Clearly, a fundamental understanding of the physics of rocketry is required in
order for the student to intelligently pursue optimization efforts and the first three
quarters or more of the course is used to develop this understanding. Once this
fundamental material has been established, approximately two weeks are spent discussing
various optimization options, explaining why GA’s are used in our work, explaining how
GA’s work and what is meant by an objective function.

Missile optimization research efforts at Auburn have incorporated models for both
liquid engine and solid rocket motor propulsion. The most easily implemented
optimization tool is the tool used to optimize various solid rocket motor applications.
Hence, the solid rocket motor optimization has represented the initial efforts to
incorporate optimization into the rocket propulsion course.

In order to model a missile in enough detail to provide even preliminary design
level accurate models, a thorough model of the internal ballistics is required.
Representative treatment of the dynamics is also necessary. The aerodynamics are also
usually important; however, in many cases, a suitable model for drag prediction is all that
is absolutely required. The dynamics and the aerodynamics for atmospheric flight are
covered in other courses and are included in the model and reviewed briefly in the course.
Also, a rudimentary structural model based primarily on thin-wall pressure vessel theory
is incorporated in the discussion and in the interdisciplinary development of the objective
function.

The solid rocket motor internal ballistics model forms the core of the modeling
needed to predict missile performance and the details of the physics behind this model are
presented and discussed in detail in the course. Some of the key elements of the solid
rocket motor internal ballistics model include: basic performance modeling using the
conservation equations; grain design for right circular perforation grains including
circularly perforated grains, star grains; wagon wheel grains, dog bone grains and
combinations of these designs.

Most of the design parameters for the optimization work discussed in this paper
are derived from the geometric grain design. Examples of schematics used to present this
material in the course are shown in Fig. 1 and the equations for the grain burn back for
both the star and wagon wheel are presented in Refs. 15 and 16.

Figure 1. Schematics for star and wagon wheel burn back analysis (Ref. 15)

Many other physical details are included in the solid rocket motor section of the
course and most of these details are included in the model. For example, propellant
characteristics, axial pressure gradients, erosive burning and grain integrity are considered.

To enhance the understanding of the physical models and the design process, a grain cross-section plotting program is demonstrated and supplied to the students. Generally, seven parameters are required to fully cover the above mentioned grain designs. Only six parameters are required for the star grain so the physical model and the coupled plotting program are set up so that if a conflict occurs in the wagon wheel or dogbone design, the design reverts to a star/cp configuration. Grain design examples obtained using the supporting software are shown in Figure 2.

![Figure 2: Sample Grain Designs](image)

**Optimization Tool**

The optimization tool is composed of a suite of legacy codes driven by a genetic algorithm. The genetic algorithm is the IMPROVE code written by Dr. Murray Anderson and the suite of legacy codes includes the solid rocket motor performance code detailed in the rocket course. The optimization tool allows the user to set up the desired scenario for optimization either through an input data file or through GUI screens. For both cases the range and resolution of the design parameters which describe the design space is defined. For all of the coursework optimizations there is some form of graphical output at the end of each successive generation. The problems selected for demonstration purposes in the class include matching a pressure time curve for a given rocket motor and optimizing the performance of a sounding rocket by matching a burnout altitude and minimizing takeoff weight.

For the pressure time match, the goal information must be entered through the GUI. For the purposes of the class demonstration, the goal function is set up to accommodate linear pressure time curves only. The initial pressure, the pressure slope, and the desired burn time are the goal inputs. The goal function is programmed to penalize all members of the population which do not have burn times within some pre-selected tolerance. The primary goal then becomes the square of the difference between the candidate design and the goal design. An example required input file to set up the GA parameters and the design space in shown in Appendix A. Note that many of the design variables for the grain cross section are set up as normalized parameters to minimize the geometric conflicts that will inevitably arise from specifying a wide design space for a complex geometry.
The students are asked to formulate their design problem by constructing an appropriate input file and setting the goal parameters through the GUI. The output is both on screen and stored in data files for post processing. A sample run demonstrating this component of the optimization content is illustrated in Figures 3-6. The screen shot shown in Figure 3 is at generation 13 where the GA has not begun to find a good match between the desired linearly increasing pressure curve and the best performing match from the family of GA solutions. Figure 4 shows the result after 40 generations with a better order of magnitude match. At generation 100 (Fig. 5) the linear profile is much more closely approximated by, in this case, a wagon wheel design. At generation 500, the match has essentially stopped improving significantly as can be seen in Figures 6 and 7. As part of the class, this optimization tool is demonstrated and then the students are asked to design the internal geometries for motors with varying pressure time histories and plot the resulting grain cross sections and motor performance.

![Figure 3: Thrust time match after 13 generations showing the best performer.](image)

![Figure 4: Best Performer for Pressure Match at Generation 40.](image)
Figure 5: Best Performer for Pressure Match at Generation 100

- Plotting curve for best performer of generation: 100
- Design parameters of this missile:
  - Parameter 1: 7.653374
  - Parameter 2: 0.539444
  - Parameter 3: 0.717173
  - Parameter 4: 10.14236
  - Parameter 5: 1.901961
  - Parameter 6: 0.899989
  - Parameter 7: 149.674
  - Parameter 8: 16.80094
  - Parameter 9: 1.700788
  - Parameter 10: 1.100399

Figure 6: Figure 5: Best Performer for Pressure Match at Generation 500

- Plotting curve for best performer of generation: 500
- Design parameters of this missile:
  - Parameter 1: 7.666667
  - Parameter 2: 0.663222
  - Parameter 3: 0.461213
  - Parameter 4: 7.265714
  - Parameter 5: 0.99999988
  - Parameter 6: 0.699999
  - Parameter 7: 24.11765
  - Parameter 8: 18.12117
  - Parameter 9: 2.845289
  - Parameter 10: 1.308000

Finished Execution
Currently displaying parameters and pressure curve for best performer of the final generation.

Figure 7: Goal Performance for Pressure Match Optimization

- Chart showing the merit of optimization over generations.
It should be noted that some of the simple design problems illustrated using this introductory optimization example can be worked by hand analytically; however, more complex pressure-time curves cannot readily be matched analytically and many non-population based conventional optimization techniques do not work well for the solid rocket motor problem because one of the design variables is the number of points or spokes which is inherently a discrete function and is not differentiable.

The second, more complicated example for the optimization content of the course involves the design of a sounding rocket. This exercise, unlike the pressure-time curve match, is multidisciplinary. For the sounding rocket to be designed even at the preliminary level, the propulsion model must be supplemented by at least simple models for the mass of the rocket, an aerodynamic model including a model of the atmosphere, and a dynamics model. A specified payload, a thin wall pressure vessel theory model for the inert components, and the grain density and geometry suffice to provide a simple mass properties model. An equation based model of the standard atmosphere and a simple one equation model for the drag provide the rudimentary aerodynamics model and the rectilinear dynamics model based on a time marching scheme is derived in class to provide the setup for the dynamics problem. The basic result of the dynamics model for vertical flight with decreasing mass, variable aerodynamic drag and gravity at a given point in the flight for a given time interval is the following:

\[
V_f = \frac{C_1(C_4 - 1)}{\sqrt{C_1 C_2 (C_4 + 1)}}
\]

where:

\[
C_1 = T - \bar{W}
\]

\[
C_2 = \frac{1}{2} \rho C_D S
\]

\[
C_3 = \frac{2g \sqrt{C_1 C_2 \Delta t}}{\bar{W}}
\]

\[
C_4 = \frac{C_1 + V_f \sqrt{C_1 C_2}}{C_1 + V_f \sqrt{C_1 C_2}} e^{C_3}
\]

In these equations, \( T \) is thrust, \( \bar{W} \) is weight (averaged over the time interval \( \Delta t \)), \( \rho \) is atmospheric density, \( C_D \) is the drag coefficient, \( S \) is the rocket cross sectional area, and \( g \) is gravity. This dynamics model provides the basic performance prediction capability necessary for altitude and velocity goals for a sounding rocket optimization problem.

Currently, the input for this case is through data files only. For the demonstration case, the program is set up to match a burnout altitude with a minimum weight sounding rocket for a given payload. An additional goal could be matching a burnout velocity. In practice this is likely to improve the realism of the design process; however, for simplicity, this additional goal was left out in this initial introduction of the optimization tool to the course. Again, enough text and graphical information is presented as the
program runs to give the user a sense of how the missile design is progressing. The external geometry, the grain cross section and a basic flight path plot are included on screen as shown in the screen shot included as Figure 8. In this particular example, the snapshot is taken at the generation 20 point. The altitude goal is 45000 ft and the key goal related parameters are included immediately beneath the altitude time plot.

![Sample results for a sounding rocket.](image)

While the on screen output is very important to the pedagogical process, this output is not suitable for professional reports. After the design process is complete the student is asked to prepare a brief but professional report on their individual unique design project assignment. To facilitate the development of these reports, the design optimization tool is set up to output data files containing critical performance and geometric data for the best performer of the final generation in the GA run. For the grain cross section, a text file containing the data for drawing the cross section as it is shown on screen is automatically written for this final best performer. The students can simply use Excel or any other plotting program to quickly generate the best performer cross section geometry. For the missile profile, the student is required to interpret the geometric output and provide their own sketch. The performance data is in a format that is easily read by a variety of spreadsheets and plotting packages.
Results and Student Response

The optimization of solid rocket motors was successfully integrated into the course by introducing the tool as a completely compiled program with a limited graphical interface rather than by asking the students to perform part of the programming task themselves. Integrating student programming into the course would be possible in a course setting allowing more extensive coverage of the material but this is not necessary for the students to understand and assimilate the benefits of the optimization content. Furthermore, this approach allows the student to focus on the engineering design problem at hand rather than on programming. This is important given the limited time allotted for design optimization in the present course format.

Student reaction to this initial effort to include design optimization has been overwhelmingly positive. The course is taught as a senior level undergraduate elective, an entry level graduate course and as an off-campus video outreach course taken almost exclusively by practicing engineers. One off-campus engineer had the following to say about the optimization content: “I thought the optimization section was an extremely beneficial section. I did not realize how important in industry optimization is until I started working in it. A few of the projects that I have worked on up here in Saint Louis have been directly involved with Optimization and I found the course work very relevant. The exposure of a topic that is often not touched in undergraduate/graduate school is a great idea. I think it would be beneficial to continue to teach it in the upcoming classes of Rocket Propulsion...”

The on campus students appreciated the format for the optimization contents as summed up in the following comment: “I really enjoyed the optimization part of the course. It was also nice that we didn’t get bogged down in programming, but instead focused on the wider variety of subjects.”

The undergraduate students are less experienced but seem to enjoy this portion of the class most as evidenced by the following critique: “I thought that the GA/Design Optimization portion of the class was very interesting and I wish that there were more of it.”
Future Pedagogical Efforts

The spring of 2006 was the first effort made at integrating optimization into the solid rocket motor content of the rocket propulsion class at Auburn University. Given the operation of the design tools implemented and the response of the students to the material, this activity is considered to be very successful and will be continued and substantially expanded in the future.

The highest priority will be to further improve the usability of the optimization tool by completing the GUI for the solid rocket motor cases. Another high priority for the next course offering will be to expand the goal selection for optimization and to modify the goal programming so that the students can directly program the goals in some way.

Another major thrust will be to incorporate the liquid rocket optimization work currently under development into the classroom setting. At the moment, liquid rocket engine instruction consumes approximately forty percent of the course time. This could easily be capped by a one week segment on design optimization for liquids given a preprogrammed optimization tool equipped with a GUI. This will likely be incorporated into the course during the next instructional cycle.

Finally, it should be noted that efforts are underway to offer the Rocket Propulsion course in an international setting during the next instructional cycle. This will bring optimization of rocket designs to the classroom in an international arena for maximum visibility and dissemination.

References


Appendix A

.false. ; micro
.false. ; pareto
.false. ; steady_state
.false. ; maximize
.true. ; elitist
.true. ; creep
.false. ; uniform
.false. ; restart
.true. ; remove_dup
.false. ; niche
.false. ; phenotype
0.04 ; niche diversity percentile goal
61742 ; iseed
0.9 ; pcross
0.002 ; pmutation
0.05 ; pcreep
1 ; ngoals
1. ; xgls(j)
1. ; domst
2550 ; convrg_chk (end of group2)
10 ; no_para
'kfuel 1' , 8.0 , 1.0 , 1.0 , .false. ; xmax,xmin,resolution,niche_par
'rpvar 2' , 0.95 , 0.1, 0.01, .false. ; xmax,xmin,resolution,niche_par
'rivar 3' , 0.99 , 0.01, 0.01, .false. ; xmax,xmin,resolution,niche_par
'nsp 4' , 13.0 , 3.0 , 2.0 , .false. ; xmax,xmin,resolution,niche_par
'fvar 5' , 0.2 , 0.01, 0.01, .false. ; xmax,xmin,resolution,niche_par
'epx 6' , 0.9 , 0.1 , 0.1 , .false. ; xmax,xmin,resolution,niche_par
'ptang 7' , 120., 0.0 , 1.0 , .false. ; xmax,xmin,resolution,niche_par
'gl 8' , 100., 1. , 0.1 , .false. ; xmax,xmin,resolution,niche_par
'rbi 9' , 10. , 1. , 0.1 , .false. ; xmax,xmin,resolution,niche_par
'diath 10' , 1.2 , 0.05 , 0.01, .false. ; xmax,xmin,resolution,niche_par
1 ; ifreq
150 ; mempops
50 ; maxgen

C ************** GA VARIABLES ***********************
C xray(1) - propellant type type
C xray(2) - propellant RPVAR: (Rp+f)/(body radius)
C xray(3) - propellant RIVAR: Ri/Rp
C xray(4) - number of star points
C xray(5) - fillet FVAR: f/Rp
C xray(6) - epsilon (star PI*eps/n) star width
C xray(7) - star point angle
C xray(8) - grain length
C xray(9) - outer radius of grain
C xray(10) - throat diameter
C ***********************************************