Cost vs Performance in Propulsion System Design

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The propulsion designer is confronted with significant difficulties in selecting rocket motor parameters in applications where both cost and performance issues exist. While not a problem in principle, there is a formidable problem in practice because of the impracticality of conducting all of the necessary propulsion tradeoffs within the context of the entire system. The propulsion designer must therefore uncouple the rocket motor optimization from the system optimization by developing a measure of propulsion cost effectiveness and by treating major interface variables with constraining relations. The context for an analysis of this problem is a small-diameter free-flight artillery rocket system incorporating a solid-propellant rocket motor. Several low-cost rocket motor approaches are compared with a conventional design. While offering unit cost savings, these low-cost approaches involve performance and reproducibility penalties. Even with a single definitive cost-effectiveness measure, it is shown that any of these designs may be regarded as optimum, depending on how the comparison is made (i.e., which constraints are imposed). Chamber pressure serves as an example of optimization of a continuous variable in the presence and absence of constraints. Again, system constraints are found to have a profound effect on optimization results.

I. The System Optimization Problem

A FREQUENT goal in propulsion design activities is that of reducing unit production cost. Unfortunately, those aspects of a propulsion system's design that contribute to low cost (as compared to alternatives) often also lead to performance losses. This duality creates the requirement to perform the propulsion design activity in the context of the entire system, since cost and performance can only be made commensurable at the system level. The propulsion designer, therefore, must also operate at the system level in facing the cost implications of any performance degradation that results from a cost saving feature in his design.

The system optimization process is widely agreed to consist of three basic steps: define the problem, establish a system model, and manipulate the model to achieve an optimum. The example to be considered here is an artillery rocket system. Since a weapon system optimization study must include the entire force structure, it is assumed that a broader study has already identified a small-diameter rocket system as having a needed role in the optimum weapons mix. The basic parameters of the desired rocket system will have been defined: deployment, types of targets to be engaged, and an approximate definition of the engagement range.

The first step in defining the artillery rocket system optimization problem is to postulate the characteristics and distribution of the target array against which the rocket system will be used during its lifetime. A level of effectiveness must be selected sufficient to neutralize, in a fixed period of time, the military threat posed by these targets. (Generally, achieving 10% to 50% attrition in the target array is sufficient.) The optimization problem is thus one of defining the system configuration that achieves this fixed level of effectiveness for the least life cycle cost.[1] Formulating the problem in terms of achieving a fixed effectiveness at minimum cost is preferred to the approach of fixing cost and maximizing effectiveness, since the former guarantees a theoretical capability to win.

The next step is to model the entire system, including the target array. It is at this stage of the optimization process that the propulsion subsystem becomes an identifiable component with parameters that can be manipulated as part of the optimization process. In principle, the entire problem with its relevant variables could be modeled mathematically as a computer code or collection of codes. For the propulsion system, major motor design parameters could be related to performance (size, weight, range, and accuracy) and directly or indirectly to the various elements of life cycle cost. Even a partially complete model, however, would consist of an enormous number of both constrained and unconstrained variables. These elements do not prevent a solution, since there are many efficient optimization techniques for solving such problems.[2] The difficulty encountered is the large number of discrete variables that require distinct models, if subsystem interactions are to be retained in the system model. Types of guidance systems or munitions are some examples of discrete variables. Each, in effect, requires a separate optimization study. In practice, time and resource constraints allow only a limited exercising of existing models, and the development of new models prior to a study is generally out of the question. The system designer must limit the variables under manipulation to those few judged to have the greatest influence on the outcome. He will be preoccupied with such basic issues as guided vs unguided rockets and, thus, will not be of much help in making propulsion design decisions. Typically, few propulsion variables are included in systems optimization. One cost-effectiveness study of a ballistic missile modeled the propulsion with two variables: specific impulse and propellant weight fraction.[3] While such a lack of detail at the subsystem level may serve the purposes of the

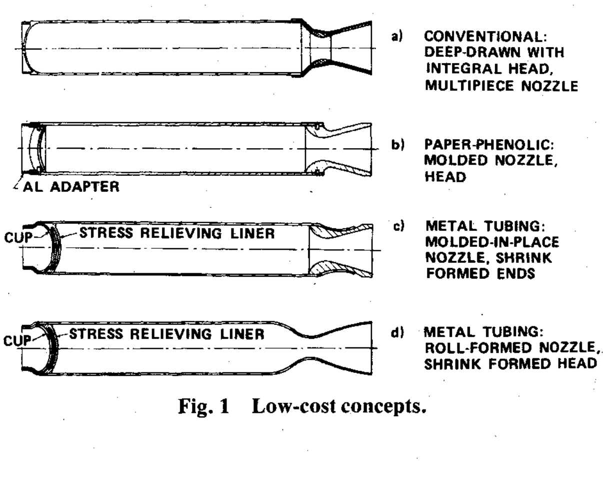

Fig. 1 Low-cost concepts.

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system designer, it provides no useful information to the propulsion designer.

The propulsion designer is thus left to his own resources in making design decisions that affect systems performance as well as unit cost. Since the propulsion designer cannot operate at the systems level, he must uncouple the propulsion optimization from the system design process. Two things must be done to accomplish the uncoupling: 1) develop a common measure of cost and performance and 2) replace the propulsion/system interface variables with appropriate constraining relations. What follows is an elaboration of the problem, with a free-flight rocket artillery system as a specific example.

II. Uncoupling the Propulsion Design Problem

The first step in uncoupling the propulsion design problem from the system design process is to define a measure of propulsion cost effectiveness. For the rocket artillery system to be considered here, such a measure is relatively straightforward. The artillery rocket system mission, as commonly defined, is to achieve a given fractional attrition against a postulated target array. For a given munition and target composition, the attrition is a function of the munition weight delivered and the delivery accuracy. The design of the rocket motor bears directly on both these parameters, since motor size and performance determine the payload weight delivered to a given range and since motor reproducibility (thrust misalignment and impulse variation) contributes to the rocket's dispersion. These considerations lead to a cost-effectiveness measure for the rocket motor: cost per pound of munitions delivered on target. In comparing motor designs with different reproducibilities, the munition delivery cost must be adjusted to account for the differing number of rounds required to achieve a given munition density on the target. The influence of dispersion on the number of rounds required is readily seen from the following approximation: if N_f is the number of rounds fired and N_t is the number of rounds impacting within the target area, then the ratio of these quantities is

$$N_f/N_t \cong 1+1.2(\mathrm{CPE}/R_t)^2$$

where CPE represents the rocket dispersion (the radius of a circle encompassing 50% of the impacts) and R_t is the radius of the target. In the area saturation role, where the target radius is much larger than the rocket dispersion, the ratio approaches unity and effectiveness is not influenced by accuracy. If specific size targets are considered, however, the system's accuracy materially affects the number of rockets that must be fired to achieve a given level of effectiveness. For the sample problem considered here, a baseline rocket system design having a maximum range of 25 km and a CPE of 250 m will be assumed for maximum range. Using an average target radius of 200 m for the array, the ratio of the number of rounds fired to rounds on target will be

$$N_f/N_t = 1+1.2(250/200)^2 = 2.875$$

Thus, nearly three rounds are required to achieve a single round on target for the baseline system. This ratio must be calculated for each distinct design approach, and the basic unit delivery cost adjusted accordingly.

The second requirement in uncoupling propulsion optimization is to replace those system interface constraints that impact propulsion design with selected constants or restraining relations. For the physical interface constraints, such as rocket length or weight, the payload length-weight relation for the selected munition and rocket diameter must be used in sizing the rocket motor to meet a desired maximum range. For the fixed rocket-length situation, the propulsion designer's task is then one of minimizing the motor-cost/payload-weight ratio subject to the constraint

$$W_{\mathrm{pay}} = f(L_{\mathrm{rkt}} - L_{\mathrm{mtr}})$$

For the fixed rocket weight case, the objective remains the same, but the constraint becomes

$$W_{\mathrm{pay}} = W_{\mathrm{rkt}} - W_{\mathrm{mtr}}$$

If both constraints exist simultaneously, then both must be applied, with only the more stringent being an equality constraint. In this manner, both the motor cost and payload capacity of a given design approach are accounted for in the selection criterion. Rocket diameter, burning duration, and possibly maximum design range are examples of system interface variables that bear on motor design and must either be fixed or treated parametrically. While this kind of treatment allows the propulsion designer to proceed with the optimization task, the expedience comes at the expense of multiplying the number of cases that must be analyzed.

III. Cost Effectiveness of Several Low-Cost Concepts

Several approaches to a low-cost motor case and nozzle for a small-diameter rocket motor[4] are depicted in Fig. 1. Figure 1a presents what may be described as a conventional approach. Here, the motor case would be produced by deep drawing and would have an integral head closure. The nozzle would be spun with a molded filled-phenolic liner. In Fig. 1b, paper-phenolic tubing is utilized in the design. Molded phenolic parts form the head closure and nozzle, with a machined aluminum casting incorporated into the head closure to serve as the mating member with the payload. Approaches using commercial metal tubing are shown in Figs. 1c and 1d. In the first of these a preformed cup is shrink-formed in place to form the head closure and a filled-phenolic insert is molded into the preformed tube to form the nozzle. The last design dispenses with the molded nozzle and instead has a flame-sprayed refractory coating over the roll-formed contour as the nozzle. All designs provide a reduced diameter section for mounting fins.

All of the unconventional low-cost approaches have inherent performance penalties. These arise because of the reduced strength/density ratio and tolerance levels of commercial tubing and the necessity of reduced chamber pressures where molded components are incorporated. The issue that must be explored is whether these low-cost concepts indeed result in low-cost rockets; in other words, what are the cost implications of reduced performance and reproducibility?

A comparison study of the design concepts in Fig. 1 was conducted with the methods outlined earlier. All designs were sized to deliver a payload to a 25-km maximum range. The diameter and motor burning duration were fixed at 6.6 in. and 2 s, respectively. Five specific design approaches were examined: 1) a conventional approach to serve as the baseline, 2) a paper-phenolic tube with molded parts, 3) heat-treated commercial pipe with a molded nozzle, 4) heat-treated commercial pipe with a coated nozzle, and 5) as-received commercial pipe with a coated nozzle. A reduced flame temperature propellant (4800°F) was required in designs 4 and 5. Rocket motor costs were estimated for a relatively large production quantity, and only recurring costs were included. Cost estimating methods that reflect differences between the design alternatives under investigation are obviously required. Of little use here are the so-called "top down" or parametric-type cost estimates, which are essentially statistical correlations of gross motor attributes and historic costs. Industrial engineering methods relating the rocket motor preliminary design to manufacturing processes and ultimately cost, such as those developed at Battelle Memorial Institute,[5] are a necessary tool in resolving the cost-performance issue. A detailed industrial engineering method was used in the present study. Nonrecurring procurement costs were judged to be largely independent of design decisions, but a more complete analysis would include those development, operating, and maintenance costs that are a function of motor design. All low-cost designs had some reproducibility degradation as well as performance penalties. The effect of this poorer thrust alignment and impulse reproducibility was incorporated in the rocket CPE, which was somewhat larger than the baseline conventional design. The CPE was calculated for each design by estimating the magnitudes of the motor variations, multiplying these variations by the corresponding rocket sensitivity, and finally root-sum-squaring the result with the remaining rocket error sources.

Several physical system constraints impact the rocket design. The first to be considered is rocket length. It will be assumed that the use of standard military containers is desired for transporting and storing rockets and will be incorporated in the overall concept of this rocket artillery system, with the result that the rocket length is limited to 96 in. In the first design study, therefore, the rocket motors were sized in conjunction with the payload weight-length relation so as to hold missile length constant at 96 in. Table 1 presents a comparison of the various design concepts sized under the constant-length constraint. The conventional design results in the highest performance on a payload weight delivered basis. The lower performance of the low-cost concepts results in increased motor length for a constant-diameter, fixed-range rocket. The end result is reduced length available for payload, and hence payload weight. In terms of motor cost, however, all of the low-cost concepts save approximately $100 per unit over the conventional design. This is a savings sufficiently large to more than offset the performance penalty, as reflected in the basic unit payload delivery cost. The same rankings are maintained even where the delivery cost is adjusted for the greater dispersion of these designs. The most cost-effective approach under the length constraint is concept 3—the commercial metal pipe case with a molded nozzle.

To explore the effect that constraints have on optimization, this study was repeated with other constraints. In one variation, the results of which are presented in Table 2, total rocket weight was held constant at that value, 215 lbm, determined for the conventional design under the length constraint. A weight constraint normally arises when the launch vehicle or resupply vehicle payload weight is apportioned among the rockets to be carried. Chamber pressure was reoptimized for all designs under the new constraint. Here again, the low-cost design approaches are more cost effective than the conventional design even while delivering less payload per rocket. The best approach is no longer concept 3, however, but concept 2—the paper-phenolic design. Also, the level of cost effectiveness achieved is greater than that under the length constraint: $5.80 per pound of munitions on target vs $6.17, a savings of over 5% in ammunition delivery cost. One way of viewing this savings is that it represents the cost of having a length-limited missile. These costs ignore any cost implications of the increased rocket length in logistics and operation, just as the weight differences were similarly ignored in the constant-length comparison.

Constant delivered payload weight is another common means of comparing various design approaches. Table 3 presents the results of sizing all designs to a constant payload weight equal to the baseline design. In this comparison, the performance penalties of the low-cost design approaches manifest themselves as increased weight and length over the baseline design. The cost-effectiveness figures indicate substantial savings with all of the low-cost concepts, however. At constant payload weight, concept 5 results in the minimum delivered-on-target cost of $5.16 per pound of munitions. This amount represents considerable cost savings over the minimum achieved under the constant rocket length or weight constraints.

Three different constraints have thus far been used, and three different design approaches have been indicated as optimum. In order to pursue this issue to its extreme, a final study was performed, with the rocket motor cost held constant. In essence, the cost savings realized by the low-cost approaches permitted increased propellant weight and, in turn, a large increase in delivered payload weight. These results are presented in Table 4. None of the low-cost designs are practical, all having unworkable length-to-diameter ratios. Where a pure motor cost constraint is used, however, the cost-effectiveness measures show dramatic differences. In this instance, yet another low-cost approach is indicated as

Table 1 Motor design comparison at constant rocket length

	Concept 1	2	3	4	5
Motor weight, lbm	88	89	100	103	114
Payload weight, lbm	127	108	119	96	91
Rocket weight, lbm	215	197	219	199	205
Rocket length, in.	96.0	96.0	96.0	96.0	96.0
Motor cost, $	324	235	233	214	212
Basic delivery cost, $/lbm	2.55	2.18	1.96	2.23	2.33
CPE, m	250	258	268	260	255
Adj. delivery cost, $/lbm	7.33	6.52	6.17[a]	6.75	6.88

[a] Optimum.

Table 2 Motor design comparison at constant rocket weight

	Concept 1	2	3	4	5
Motor weight, lbm	89	90	99	105	113
Payload weight, lbm	126	125	116	110	102
Rocket weight, lbm	215	215	215	215	215
Rocket length, in.	95.6	102.9	94.6	100.7	103.6
Motor cost, $	320	243	231	216	219
Basic delivery cost, $/lbm	2.54	1.94	1.99	1.96	2.15
CPE, m	250	258	268	260	255
Adj. delivery cost, $/lbm	7.30	5.80[a]	6.26	5.93	6.34

[a] Optimum.

Table 3 Motor design comparison at constant payload weight

	Concept 1	2	3	4	5
Motor weight, lbm	88	91	102	110	122
Payload weight, lbm	127	127	127	127	127
Rocket weight, lbm	215	218	229	237	249
Rocket length, in.	96.0	104.7	98.6	107.2	113.3
Motor cost, $	324	245	235	223	222
Basic delivery cost, $/lbm	2.55	1.93	1.85	1.76	1.75
CPE, m	250	258	268	260	255
Adj. delivery cost, $/lbm	7.33	5.77	5.82	5.33	5.16[a]

[a] Optimum.

Table 4 Motor design comparison at constant motor cost

	Concept 1	2	3	4	5
Motor weight, lbm	88	170	188	211	237
Payload weight, lbm	127	371	392	403	336
Rocket weight, lbm	215	541	580	614	573
Rocket length, in.	96.0	221	201	222	240
Motor cost, $	324	324	324	324	324
Basic delivery cost, $/lbm	2.55	0.87	0.83	0.80	0.96
CPE, m	250	280	305	285	333
Adj. delivery cost, $/lbm	7.33	2.92	3.15	2.75[a]	4.14

[a] Optimum.

Table 5 Optimum cost effectiveness under various constraints

Constraint	Munition delivery cost, per lbm
Rocket length	$6.17
Rocket weight	$5.80
Payload weight	$5.16
None (cost)	$2.75

optimum. A pure cost constraint leads to the lowest-cost rocket motor per pound of munitions delivered.

While these four sets of comparisons did not answer the question as to which design approach is optimum for an artillery rocket system (the question is probably unanswerable in precise terms), it illustrates the profound influence of constraints on the optimization of discrete systems. In summary, the optimum cost effectiveness achieved under the various constraints are given in Table 5. The first three constraints result in essentially similar rockets, while the fourth produces a rocket in an entirely different size category, and including this latter case in the ranking is unfair. The point is made, however, that rocket length and weight constraints (especially length) place a premium on performance and lead to more expensive rocket designs. The propulsion designer should therefore challenge the length and weight constraints to insure that their impact on rocket cost is at least offset by cost savings in other aspects of the system.

IV. Optimization of Continuous Variables

System constraints also impact the optimization of propulsion parameters within a particular design approach. As an example of the continuous variable case, consider the problem of selecting an optimum operating chamber pressure. Figure 2 presents the results of a sizing study with chamber pressure as the motor parameter and payload weight as the system parameter. Low-cost concept 3 was used as the motor design approach. Range is fixed at 25 km and burning duration at 1s. Figure 2 was developed by sizing a series of motors designed at discrete operating chamber pressures to deliver the indicated payload to 25 km. The payload length-weight relation, together with motor size and weight, was used to determine overall rocket length and weight. Typical length and weight limits are shown for a 6.6-in.-diam round, based on a standard military container length, launch vehicle carry weight, and number of rounds per launcher. Only payload weight need be considered as the cost-effectiveness criterion, since rocket motor cost does not vary significantly over the chamber pressure range. Maximum payload weight is delivered by a design that borders simultaneously on the rocket weight and length constraints, at the corner of the constraint rectangle. For this case, maximum payload performance is achieved at 1800 psi. Whether a particular rocket application is weight-limited and/or length-limited will be sensitive to diameter. A relatively small increase in diameter (5%) would displace the curves of Fig. 2 sufficiently downward to remove length as an operating constraint. A lower

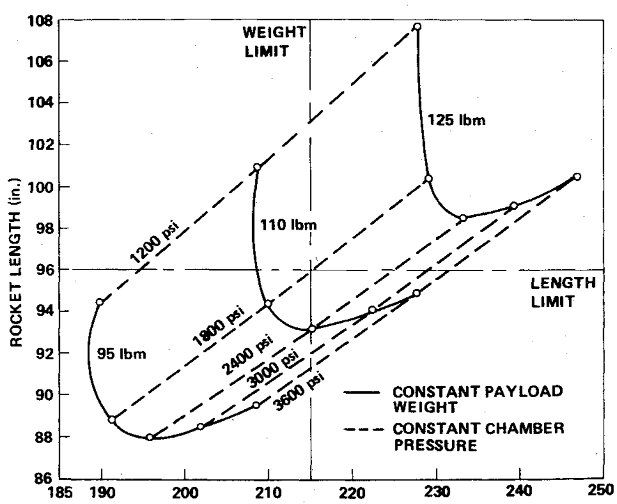

Fig. 2 Chamber pressure optimization.

chamber pressure would be optimum, not because of a change in propulsion efficiency, but because of a change in the relative importance of weight and length. If weight is the sole constraint, optimum chamber pressure tends to be low—approximately 1500 psi in this case. High chamber pressures, on the other hand, minimize length, and 2400 psi would be the approximate optimum in the length-constrained case. Since length constraints lead to more expensive, performance-driven design approaches, selection of round diameter should include the length-constraint consideration.

V. Conclusions

Methodology has been presented which allows the propulsion designer to operate at the systems level in making design decisions. With an artillery rocket as an example, a criterion for propulsion system cost effectiveness is developed which incorporates both rocket motor cost and performance in a single measure. The system interface variables are replaced with constraining relations that are treated parametrically or with selected constants. While not providing a definitive means for making propulsion design decisions, the influence and cost implications of various constraints are made clear.

Selected constraints common to most systems were imposed in a design study that compares several low-cost motor design approaches. Each constraints leads to a different optimum design approach. The system constraints were found to rank, from most costly to least costly, as follows: rocket length, rocket weight, constant payload weight, and constant motor cost. Weight and length constraints are easily incorporated in the optimization of continuous variables, such as chamber pressure, but here again constraints dictate the optimum.

The application of this methodology to situations other than that provided in the example lies in the ability to uncouple the propulsion optimization from the system design process. All that is required are a measure of propulsion cost effectiveness and constraining relations to represent the system interface. In the case of strategic systems, for example, cost effectiveness could be measured in terms of propulsion cost per value of targets covered. Major constraints would most likely be in the form of fixed payload weight and missile volume. Constraints on energy management may also be dictated by the guidance and control and launcher requirements. Once this uncoupling is accomplished, propulsion design activities can proceed on a pure propulsion requirement.

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