EXAMINATION OF A TORPEDO PERFORMANCE SPACE AND ITS RELATION TO THE SYSTEM DESIGN SPACE

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ABSTRACT

In historical torpedo design, mission analysis, which relates torpedo performance to mission success, has been used as a stand-alone tool to derive specific torpedo performance requirements. These performance requirements must then be met by the torpedo designer. However, the incorporation of mission analysis into the engineering design of a torpedo system grants more freedom to the designer. The designer can immediately see the effects of design variable changes on mission success, and can infuse new tactics in addition to new technologies to expand the available design space. This paper serves to explore the performance space of a torpedo, then relate this performance space to the design variables by mapping the performance space directly to the design space and design variables. The paper also studies how granting the designer control of weapon tactics expands the design space, allowing the torpedo and its tactics to be concurrently optimized. This new approach results in significantly greater design freedom and the ability of the find a system-level global optimum.

INTRODUCTION

In the current Navy environment of undersea weapons development, the engineering aspect of design is decoupled from the development of the tactics with which the weapon is employed. The current method calls for a group of intelligence experts and warfighters, drawing from knowledge that includes experience with previous weapons systems, wargaming scenarios, and threat assessments, to generate a preliminary set of "desired" torpedo attributes. Warfare analysis groups then use complex engagement programs and tactical considerations to refine these preliminary attributes into point performance requirements for a future torpedo system, i.e., specific maximum velocity, range, and turn rate. In addition, the requirements often include a desire to minimize vehicle traits such as radiated noise, with constraints placed on maximum allowable noise. Torpedo designers then use engineering analysis tools to translate these requirements into feasible torpedo designs that meet the specified criteria. This process is detailed in Figure 1.

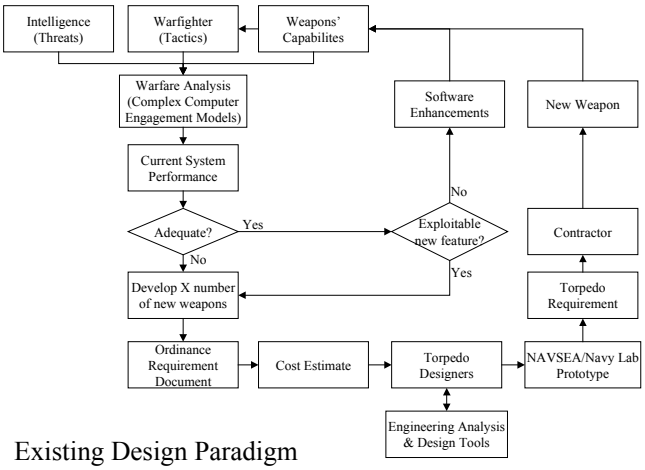


Figure 1: Existing paradigm for undersea weapon optimization and design

Unfortunately, from the total systems perspective, this design paradigm may not produce optimal designs. For one, it leads to a situation in which the tactics with which a weapon is employed are developed independently from the weapon itself. The tactics are generally derived not from design knowledge of potential systems, but from experience with the current operational system, in conjunction with threat assessments, to develop required torpedo performance attributes to best defeat future threats. These performance attributes are set as requirements and passed down to torpedo designers, who then use their engineering models and available technologies to create a torpedo system that meets the analysts' specifications. Once this newer and more capable torpedo is introduced into service, the Fleet will often create a new set of tactics that best utilizes the capabilities of the new system. The tactics are therefore continually developed

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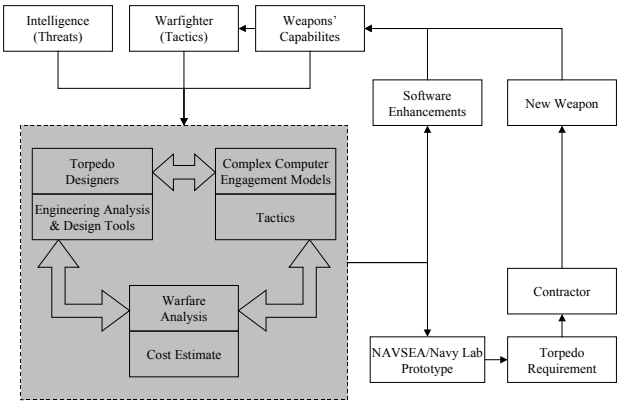
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using a torpedo with static performance. This system of tactics development, then torpedo design, then tactics re-development creates a never-ending cycle in which the weapon system is never truly optimized for the tactics with which it is employed. This lack of interaction between the warfare analyst and the weapon designer prevents the weapon system from reaching its greatest potential effectiveness.

Another drawback of this system is that weapon requirements are given to torpedo designers as a point condition, i.e., a specific speed and specific range are given. These point conditions limit the torpedo designer to developing a torpedo that fits into a tightly constrained design space, curtailing design freedom and excluding potentially feasible designs.

Therefore, to truly optimize a weapon system, the tactical employment of the weapon and engagement models must be considered *concurrently* with the engineering analysis of the weapon. This introduces a new paradigm, in which mission analysis and weapon design are considered simultaneously. The inclusion of mission analysis, and the exploration of different combinations of tactics and performance, allows for the creation of an optimal weapon system. In addition, instead of designing to a rigid set of point requirements, the designer will now have the flexibility to adjust both target performance attributes and tactics to reach the same overall performance, greatly expanding the design space and generating more freedom for the design process.



Proposed Design Paradigm

Figure 2: Proposed paradigm for undersea weapon optimization and design

In this paper, the authors illustrate an environment in which the effects of changes in engineering parameters are analyzed to determine their impact on overall torpedo effectiveness. This process is accomplished by linking a conceptual torpedo design program with a submarine engagement simulation program. Thus, the linkages between design variables, weapon performance, and tactics can be more thoroughly understood, and a vehicle with the greatest overall effectiveness can be created. This new paradigm is illustrated in Figure 2.

COMPUTER ANALYSIS TOOLS

Two computer programs were used to carry out the analysis. The first of which, TOAD (Torpedo Optimization and Design), is a conceptual sizing and synthesis program for torpedoes that relates physical torpedo design variables to torpedo performance and size. The program takes inputs such as outer diameter, operating depth, energy section length, power density, and motor horsepower. It then calculates the overall torpedo length and weights, which are often constraints for launcher compatibility, and torpedo performance metrics, such as maximum velocity, range, and radiated noise. TOAD currently has the capability to analyze three distinct types of torpedoes: an all-electric torpedo, an electric torpedo with an integrated motor-propulsor (IMP), or a Stored Chemical Energy Propulsion System (SCEPS) torpedo.

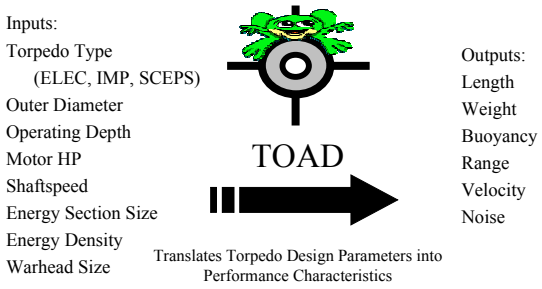


Figure 3: Inputs/outputs in TOAD

The second computer tool is a submarine engagement model, called the Advanced Collaborative Engagement Model (ACEM). ACEM was created at the Naval Undersea Warfare Center to provide torpedo designers with a means of doing simple analysis of sub-on-sub engagements and torpedo performance. The computer model works by assuming that two submarines approach each other at a random angle, with random headings for the submarines. Each submarine carries a single torpedo. The blue, or "friendly", submarine is given a slight acoustic advantage over the red, or "threat" submarine. Due to this acoustic advantage, the blue submarine always fires first in an encounter. After firing at the red submarine, the blue submarine immediately retreats from the red submarine. At the moment that the red submarine first hears the incoming torpedo, it fires its own torpedo down the same bearing as the incoming torpedo, and then flees from the

incoming threat. Then, based upon the current geometry, torpedo attributes, and submarine characteristics, the engagement model determines if either the blue or the red submarine is hit. An example ACEM encounter is illustrated in Figure 4. In order to generate a result that is continuous and not simply on/off, the model runs several randomly generated initial geometries for each simulation. ACEM then calculates two parameters, both ranging between zero and one:

- P_{kill} (Pk): The fraction of starting geometries from which the red submarine is hit. This is an indicator of how successful the friendly submarine is at striking the target. A Pk of 1.0 represents a 100% mission success rate.
- $P_{counter\text{-}kill}$ (Pck): The fraction of starting geometries from which the blue submarine is hit. This is an indicator of how successful the friendly submarine is at evading the counter-strike from the threat submarine. A Pck of 0.0 represents 100% mission survivability.

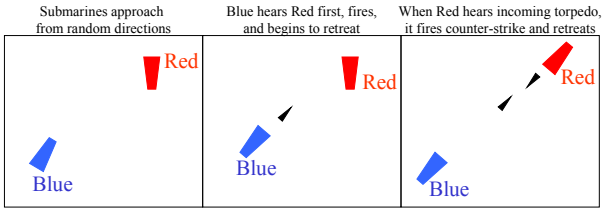


Figure 4: Schematics of an ACEM engagement

In order to run an engagement, ACEM needs two types of inputs. The first set of inputs consists of torpedo performance characteristics such as maximum velocity, maximum range, turn-rate, generated noise, and sonar performance. The second set contains tactical considerations. These tactics inputs drive how the torpedo is be employed by the blue submarine. The tactical parameters include a fire-angle offset, a slower than maximum initial torpedo speed (and hence a lower radiated noise), and a specification of the distance to travel at the slower velocity. Thus, instead of firing directly at the threat submarine, the submarine may now fire the torpedo at some angle away from the submarine, letting the torpedo close at a slower and quieter speed. Then, after some prescribed distance, the torpedo will turn into the threat submarine and close at maximum speed. This is illustrated in Figure 5.

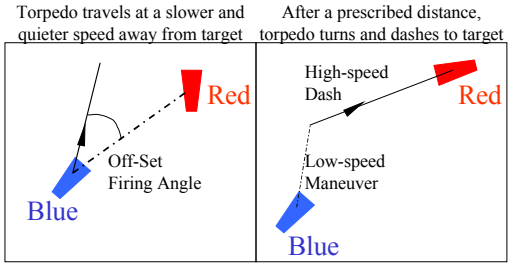


Figure 5: Tactical parameters employed in ACEM

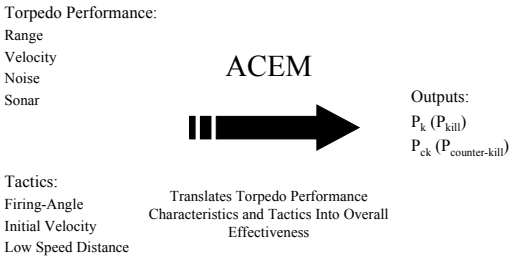


Figure 6: Inputs/output in ACEM

ACEM is not a fully-developed engagement model. For ease of use, it was desired to maintain ACEM as an unclassified program, as such, the physics were kept as simple as possible, with simple acoustics and only 2-D motion. In addition, a complex tactical environment was excluded in favor of a simpler set of tactical parameters, though these parameters were chosen because they create a significant variation in torpedo performance. ACEM is not intended to be a tool to replace those used by the engagement community, but simply a proof-of-concept of the advantages of concurrently examining the design space and requirements space of a torpedo system.

Note that TOAD and ACEM are completely separate computer programs, with completely separate tasks. TOAD, which is illustrative of a analysis tool used by the design community, maps torpedo design variables to torpedo performance. ACEM, on the other hand, is a tool that is indicative of those used by the simulation community, which uses torpedo performance characteristics, along with tactical considerations, to determine the actual effectiveness of the system. It is the mating of these two stand-alone tools that will create a powerful synergy, allowing for the true optimization of both torpedo design and tactical implementation to best meet a given operational scenario.

RESEARCH TASKS

This paper focuses upon three tasks to further understand the relationship of the performance space to

tactics and design variables. The first task was to explore the behavior of Pk and Pck as a function of the torpedo performance variables, i.e., determine how Pk and Pck changed as the torpedo velocity, range, and noise were varied. The second task was to take this variation in Pk and Pck and study the effects of altering tactics. Task 2 answers the questions: Does the variation of tactics open up or shrink the design space? How does the design space change? The third task involved actually mapping the design variables (motor HP, energy section size), through the performance characteristics (speed, range), to Pk and Pck values. The decision-maker could then determine exactly how the design variables, i.e., the variables over which the decision-maker has control, affect the overall performance of the system.

RESULTS

Performance Contours

In order to simplify examination of the requirements space, design contours were generated using only three torpedo performance parameters: torpedo range, torpedo velocity, and torpedo radiated noise. These three variables were selected because they are major drivers on Pk and Pck and because they match the performance parameters that are most accurately calculated by TOAD. The other torpedo performance variables, notably turn rate and sonar performance, were kept constant. Also, for the initial examination into the performance variables, the tactics remained fixed. The torpedo tactics consisted simply of a maximum speed dash directly to the target. The design bounds of the performance variables, shown in Table I, were chosen to include a host of various torpedo types, from extremely quiet torpedoes (i.e., stealth systems) to super-fast (similar to supercavitating systems) and very long-range systems. Table I also shows the values for the red torpedo, which were held fixed throughout the analysis.

Table I: Fixed values and variable ranges in ACEM

	Directivity Index	Beam Resolution	Beam Width	Turn-rate		Range		Radiated Noise	Maximum Velocity	
	dB	deg	deg	deg/sec / m/s	knot/sec / m/s	meters	nautical miles	dB	m/s	knots
	FIX	FIX	FIX	FIX		VAR		VAR	VAR	
Blue Low	50	5	20	1.944	1.0	10000	5.4	80	15	29
Blue High	50	5	20	1.944	1.0	55000	29.7	155	150	292
Red Torp	50	5	20	1.944	1	22687	12.3	155	33.4	65

In examining the resulting values of Pk (Figure 7 through Figure 9), it is evident that over most of the design space Pk has a value of either zero or one, i.e., either no kills for any of the starting geometries (Pk=0.0), or a kill regardless of the starting geometry (Pk=1.0). The region in which there was variation in Pk had very large gradients, meaning that a torpedo's performance moves nearly discontinuously from a region of Pk=0 to a region where Pk=1. Since the gradients are so steep, it is unlikely that many torpedo designs would lie in the region of varying Pk. As a result, Pk can be thought of as a constraint of Pk=1. This nearly discontinuous change can be seen in Figure 7, where contours of constant Pk are drawn. Note the steep transition from Pk=0 to Pk=1. Figure 8 illustrates this steep transition in a one-dimensional analysis, where Pk is only a function of torpedo velocity. The cluster analysis in Figure 9 also depicts the step-change nature of Pk. This figure was created by randomly generating torpedoes and plotting the results.

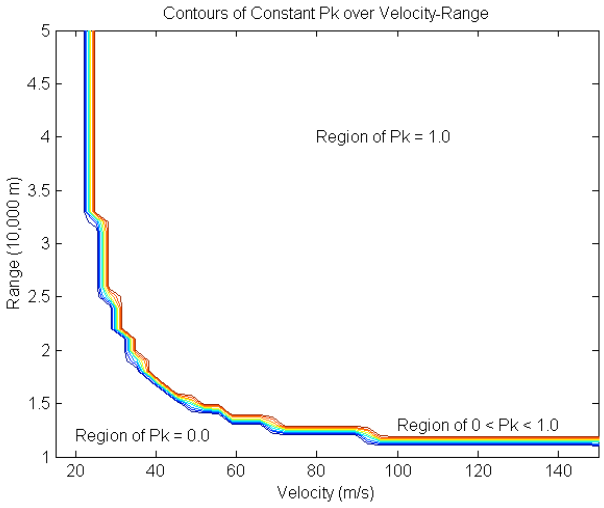


Figure 7: Contours of constant Pk

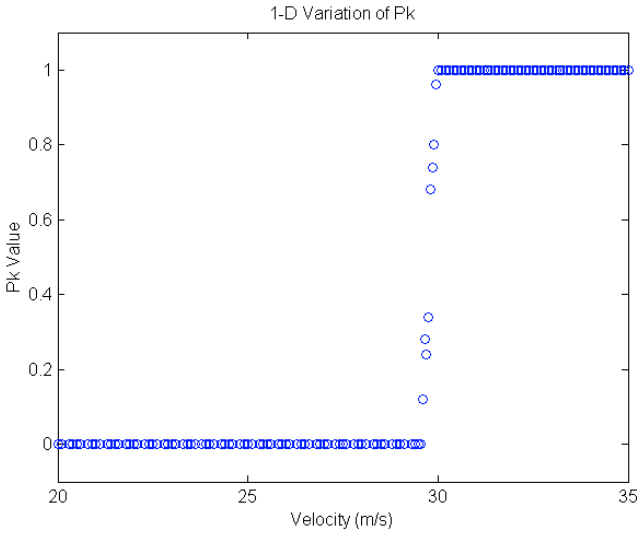


Figure 8: 1-D variation of Pk (range = 25,000 m)

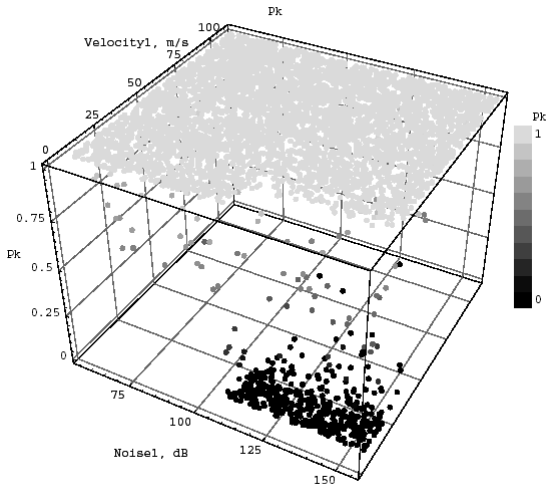


Figure 9: Variation of Pk with randomly generated torpedo characteristics, variation with torpedo velocity and noise is shown

In contrast to Pk, which has been shown to have very steep gradients, Pck has more gradual gradients. As evidenced by Figure 10 and Figure 11, there is a gradual change in Pck as a function of torpedo performance. Because of this, Pck is better treated not as a constraint, but as an objective to be minimized.

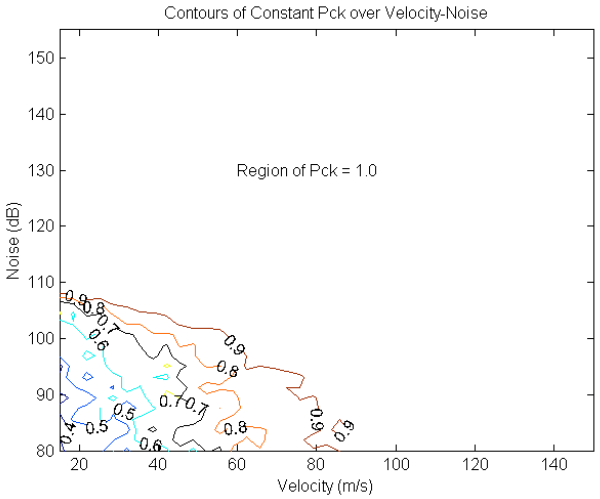


Figure 10: Contours of constant Pck as a function of torpedo noise and velocity

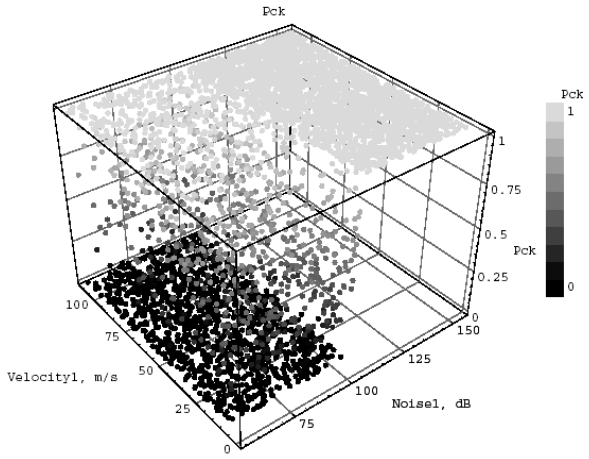


Figure 11: Variation of Pck with randomly generated torpedo characteristics, variation with torpedo velocity and noise is shown

As a result of the observed behavior of Pk and Pck, the torpedo design problem can now be formulated with Pk treated as a constraint and Pck as a value to be minimized. This new problem requires the design of a torpedo that meets the Pk=1 constraint and has a minimum value of Pck (i.e., a torpedo that always defeats an opponent while maintaining maximum survivability for the attacking submarine). Figure 12 shows contours of Pck with an overlaid Pk constraint line. The new "design point" is located on the Pk constraint at the location where Pck is minimized.

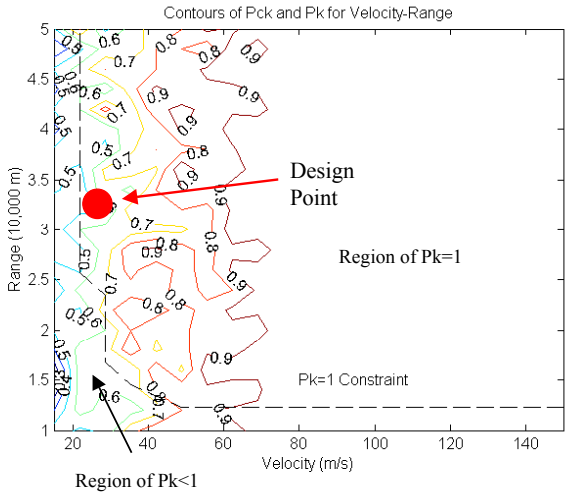


Figure 12: Contours of Pck overlaid with Pk=1 constraint

Infusion of Tactics

The next step in the analysis was to explore how the performance space behaved with the application of

different tactics. As a first analysis, the previously generated Pk and Pck contours were re-calculated with a discrete change in tactics. Instead of using a straight-on shot, the torpedo was fired at an angle of 30 degrees to the right of the target and traveled at a speed equivalent to ½ of the maximum torpedo speed (with corresponding decrease in torpedo noise). The torpedo traveled in this manner for 3,000 meters and then turned and closed at maximum speed toward the target. The initial target separation was 10,000 meters. These parameters are shown in Table II.

Table II: Tactical parameters varied

	First Data Set	New Data Set
Original Velocity	Maximum Vel.	1/2 Maximum Vel.
Original Launch Angle (wrt target)	0 deg	30 deg
Distance to travel at off-angle	0 m	3000 m

This change in tactics had a noticeable effect on Pk and Pck. In louder torpedoes, the inclusion of an off-axis firing angle made it more difficult to reach a Pk of 1.0 (Figure 13). This increase is intuitive, as the torpedo is now traveling further out of its way to reach the target. On Pck, the effects of changing tactics are even more critical. Changing the tactics significantly lowers the Pck at almost every point, as can be seen when Figure 14 is compared to an identical run with no tactics (Figure 12). Again, this response is intuitive, by shooting away from the threat submarine, it is more difficult for the threat to target you with his torpedo, however it may be more difficult for your torpedo to reach the target.

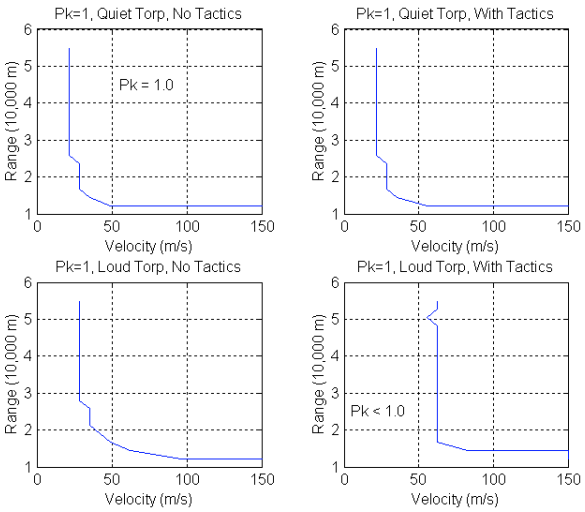


Figure 13: Variance in Pk=1.0 constraints due to change in tactics

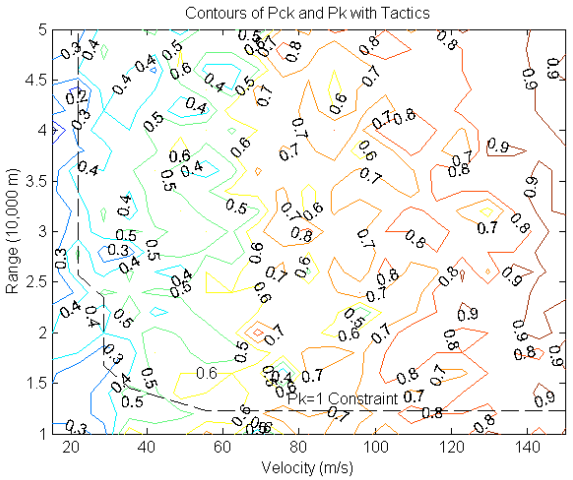


Figure 14: Contour of Pck with overlain Pk=1 constraint for example case employing torpedo tactics

Another study regarding tactics was done where the parameters were all randomized in a Monte Carlo fashion. The results are given in Figure 15 and Figure 16. Again there is a clear demarcation of Pk in Figure 15 and a smoother transition for Pck in Figure 16. For Pk, any speed combination other than a loud, slow torpedo results in a good Pk (for a fixed range). For Pck, the best submarine survival occurs when the torpedo is launched at a high angle from the threat submarine and continues along this vector for a long distance. This data does presume that the torpedo is quiet on its first leg (less than 105 dB). For louder torpedoes, it was discovered that there was no advantage to shooting off-angle.

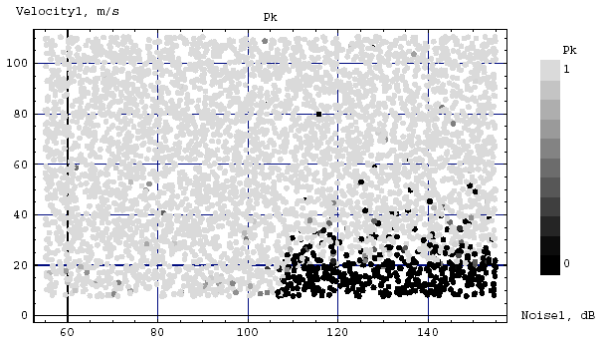


Figure 15: Variation of Pk from altering initial velocity and initial noise

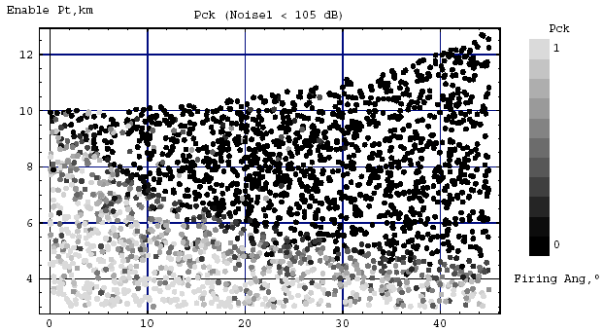


Figure 16: Variation of Pck by changing the enable point and the firing angle, note the results shown are for torpedoes whose initial noise is less than 105 dB

Relation to Design Space

The torpedo design program, TOAD, was then used to relate these performance contours to the actual torpedo design variables. A sample contour of the design space as constructed by TOAD for a SCEPS torpedo is shown in Figure 17. The contours show how the torpedo range and velocity vary as a function of input parameters for the engine.

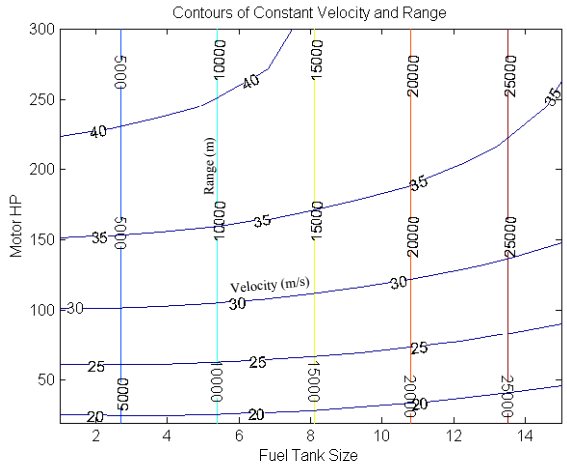


Figure 17: Design space contours relating energy section size and motor HP to velocity(m/s) and range(m)

Under the old design paradigm, a decision-maker would have been given requirements for specific values of range and velocity, along with a constraint on total length. The decision-maker would then look at the contours and choose the design variable settings that meet this criteria. However, under the new paradigm, instead of being constrained to a single design point, the decision-maker can use the earlier ACEM data to overlay Pk and Pck contours directly onto the design variables. This will give the decision-maker a greater understanding of the consequences of the design variables and more freedom in choosing a design that meets the appropriate criteria. This mapping of ACEM Pk constraints and Pck contours onto the design variables is made in Figure 18. The decision-maker can now quickly see how design variables affect the overall torpedo performance through Pk and Pck.

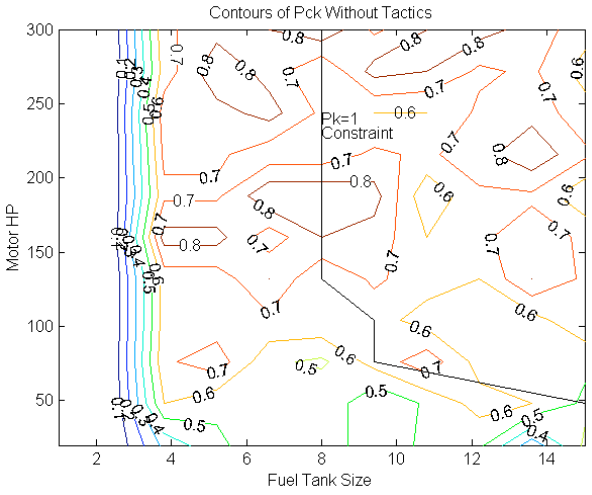


Figure 18: Contours of Pck with overlain Pk=1.0 constraint for a torpedo design space without tactics

The decision-maker can further expand his or her design options by infusing tactics into the design process. As shown in Figure 19, by including the simple set of tactics used earlier (offsetting the firing angle by 30 degrees, running at ½ velocity), the Pck contours are dramatically changed, granting additional freedom to the designer to meet overall system effectiveness requirements.

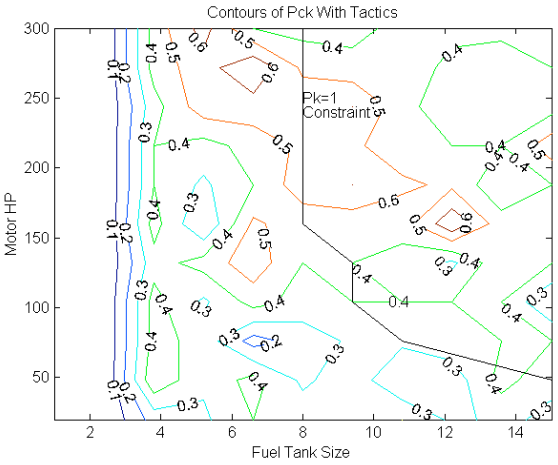


Figure 19: Contours of Pck with overlain Pk=1.0 constraint for a torpedo design space with tactics

Sampling / Meta-Modeling Difficulties

This paper examined only a small subset of the overall performance variables – velocity, range, and noise. The design study was limited to these performance variables not only because TOAD has the greatest fidelity with these variables, but also because of the poorly behaved nature of the performance space.

For one, designs of experiments and response surface methods have trouble capturing the 0/1 nature of both Pk and Pck because neither method captures plateaus very well. In the case of Pk, a method needs to be developed to search out and evaluate a constraint in multiple dimensions, i.e., a system must be generated that will determine the contour (or surface) of Pk=1 for every performance variable and tactics setting.

In addition, there is considerable difficulty in building a meta-model to represent the design space for Pck. Because of the way that Pck is calculated in ACEM, each independent set of torpedo variables and tactical settings must be evaluated by running a Monte Carlo simulation around random starting geometries. It is this repetition of runs that gives a value to Pck, calculated as the fraction of counter-kills divided by the total number of starting geometries. However, this Monte Carlo technique often creates significant noise if the number of Monte Carlo runs is not sufficiently large, i.e., if design points are repeated, the Monte Carlo method with an insufficient number of runs will generate different answers. This Monte Carlo-generated noise is the source of much of the jaggedness and seeming randomness in the contours of Pck. By increasing the Monte Carlo runs, one can smooth the contours, as illustrated Figure 20 and Figure 21. Figure 20 shows how both the average error and maximum error decrease for an increasing number of Monte Carlo runs. As the number of runs goes to infinity, the error goes to zero, i.e., there is complete repeatability in the experiment. Figure 21 compares two sets of ACEM contours, one run with the number of Monte Carlo runs set to 500, and the other to 10,000. The contours with more Monte Carlo runs are significantly straighter, illustrating the extent to which the Monte Carlo noise affects the system. Therefore, a trade-off exists between doing more runs with fewer Monte Carlos at each point, thereby generating more noise but having more DoE points, or by doing fewer runs but with a greater number of Monte Carlos for each case, thereby creating a system with fewer points, but less noise.

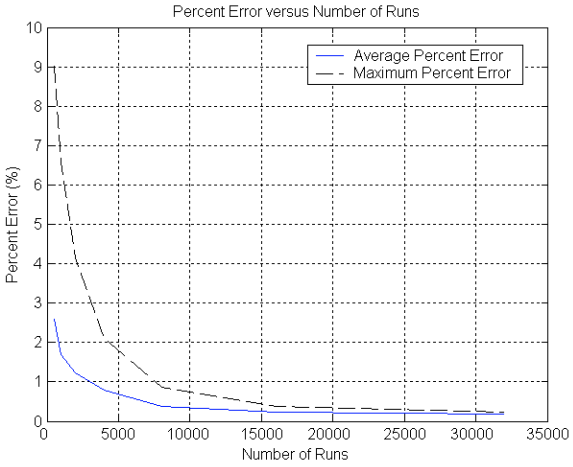


Figure 20: Error in ACEM results as a function of number of Monte Carlo runs

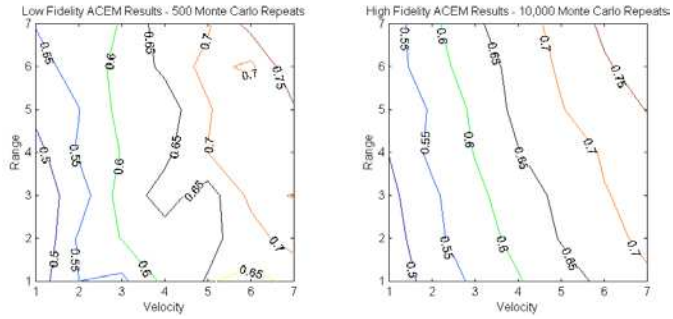


Figure 21: Non-dimensionalized ACEM contours for two comparison runs, 500 Monte Carlo repetitions on the left, 10,000 on the right

The noise generated by the Monte Carlo error makes it very difficult to generate a response surface from a traditional Design of Experiments performed around the design space. An example of such a failed attempt is given in Figure 22, where a 150 point Design of Experiments around 6 variables is compared to a full-factorial examination in two dimensions. The Design of Experiments clearly does not capture the performance space.

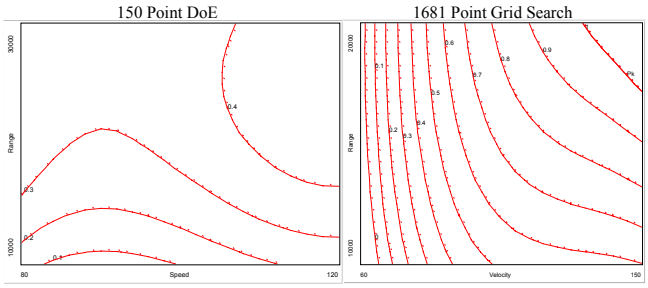


Figure 22: Comparison of contours created from 150 point DoE (left) to a 1681 point full-factorial (right)

FUTURE WORK

There are two tasks that need to be completed to facilitate the incorporation of this methodology into a complete torpedo design process. First, TOAD needs to be enhanced, so that it can reasonably calculate all of the parameters that are required by the engagement model. The torpedo design program is key to the design trade-offs, as many of the performance characteristics suggested by the engagement model (i.e., a super-fast *and* super-quiet torpedo) will be judged as technically infeasible by a torpedo design program. Therefore a fully functional torpedo design program is essential to model the many trade-offs between system performance and tactics settings. In addition, the incorporation of a cost model will add a second criterion to the optimization problem – minimization of cost along with Pck.

Because of the behavior of both Pk and Pck, traditional designs of experiments and response surface methods inadequately capture the behavior of the engagement model. As a result, studies are limited to only a few dimensions that can be explored with extensive Monte Carlo or full-factorial studies. In order to expand the system to include more torpedo performance parameters and more tactical parameters, a more effective sampling and meta-modeling system is required. Once this is accomplished, all of the design and tactical parameters can simultaneously be optimized to calculate a robust, yet global, optimum.

CONCLUSIONS

This paper demonstrates that even a simple engagement model can be used to create a new paradigm for undersea weapons design and optimization. Instead of giving fixed performance requirements to the weapon designer, it is desirable to step back a level, giving the designer a Pk / Pck requirement and access to an engagement model. This new process will allow for more design freedom and flexibility in the development of future torpedo systems. In addition to coupling an engagement model with the design tool, the inclusion of tactics as actual design variables has a great impact on the design process. Including these tactical parameters opens up the design space, creating additional options in the decision-maker's quest to design a reliable, yet effective, weapon at low cost. The integration of all facets of torpedo usage into early decision-making: torpedo design parameters, engagement modeling, and tactics selection, allows for the synergies of all the analyses to combine to create a globally optimal torpedo design.

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