

A Conceptual Design Environment for Technology Selection and Performance Optimization for Torpedoes

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ABSTRACT

The Torpedo Optimization, Analysis, and Design (TOAD) program is introduced as a parametric sizing and synthesis tool for torpedoes. Response surface methodology is introduced as a means for efficiently modeling the design space for torpedoes. Response surface equations are produced from the new thermal analysis section to model the design space for a Stored Chemical Energy Propulsion System (SCEPS) powered torpedo. Comparisons are made between SCEPS and electrically powered torpedoes, as well as between different SCEPS engine parameters. The design methods of the Aerospace Systems Design Laboratory (ASDL) are introduced for developing computationally efficient metamodels for the physics-based analysis codes used in design. Response surface methodology is shown to be an effective way to model a SCEPS powered torpedo.

INTRODUCTION

An object-oriented conceptual design architecture for torpedo design is under development by the Aerospace Systems Design Laboratory (ASDL) at Georgia Tech. This environment, known as the Universal Torpedo Model (UTM), incorporates the Torpedo Optimization, Analysis, and Design (TOAD) program, a conceptual sizing and synthesis code, as a major component of the envisioned suite of tools. TOAD models the torpedo system in logical manner via a modular decomposition of the torpedo into sections corresponding to its physical functional components. TOAD was developed out of the need for an appropriate parametric sizing and synthesis program for torpedoes that could be integrated into the design methodology under development at ASDL. Many of these methods have been successfully applied to aircraft and are being transitioned to the design of naval and marine systems. This paper introduces the design methods developed by ASDL and the TOAD program and uses them to perform a comparison study of thermal and electric torpedo propulsion systems.

ASDL DESIGN METHODOLOGY

Traditionally, designers have used historical databases as a basis to predict how a new design will behave. This historical regression is adequate if the design parameters of the new concept fall within the historical limits. However, if the new concept is an idea that falls outside of the known boundaries of the historical data, the level of confidence in the results of historical regression may be unacceptable. For these instances, physics-based analytical codes are needed to yield results with acceptable fidelity. However, these physics-based codes are often laborious and time-consuming to run.

ASDL methodology borrows from several disciplines in its approach to the problem, including biology, agriculture, and manufacturing. A design of experiments is set up in order to sample the design space in an efficient fashion, and response surface equations are used to model the various output responses produced by the analysis code. If the response surface metamodel is an accurate surrogate for the physics-based analysis, then tradeoffs can be made and various scenarios can be tested on the fly using the metamodel, thus eliminating the need to go back to the analysis code and rerun each case, saving time and money for the decision makers. This capability also allows the designer to produce a product that is robust to changing requirements, instead of one that is optimized only for a single point in the design space.

The metamodeling process follows these steps:

1. The designer decides which input variables are applicable to the exploration of the design space.
2. A screening test is performed to determine which input variables contribute the most to the variability of the responses. This is done by linearly regressing the outputs of the analysis code to allow the designer to observe the first order effects of the input variables on the responses.

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Only the input variables with the greatest amount of influence on the variability of the response are retained for further study. A Pareto chart, as shown in Figure 1, measures the influence of the input variables. The dotted lines denote percentage of variability in 20 percent increments.

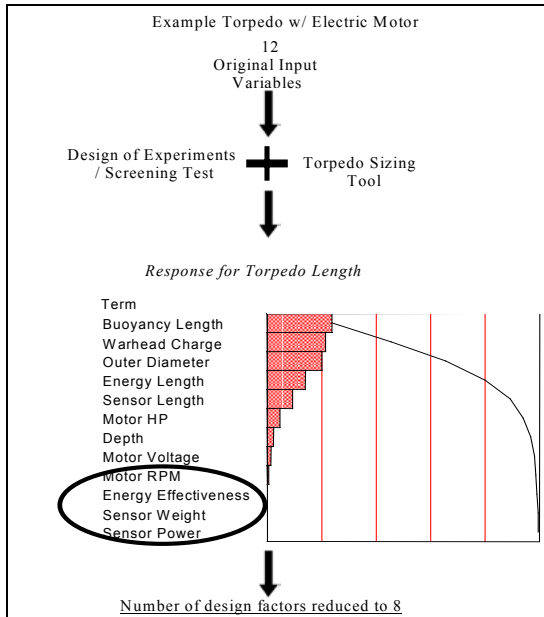


Figure 1: Pareto Chart for Reduction of Input Variables

- Response surface equations are built around the variable set. Response surface methodology is a multivariate regression technique developed to model the response of a complex system using a simplified equation. It is based on design of experiments methodology that yields maximum investigative power for a given amount of experimental effort. Typically, the response is modeled using a second-order quadratic equation, though occasionally other terms may be necessary to produce a good fit. These second-order equations typically take the form:

$$R = b_o + \sum_{i=1}^k b_i x_i + \sum_{i=1}^k b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^k b_{ij} x_i x_j$$

where b_i are the regression coefficients for the first degree terms, b_{ii} are the coefficients for the pure quadratic terms, and b_{ij} are the coefficients for the cross-product terms.

- Goodness of fit is evaluated for the response surface equations. This is performed via plotting the actual responses generated by the analysis code versus the responses predicted by the response surface equations. A scatter plot of the residual

versus the values predicted by the response surface equations is then generated. A good model fit is indicated if the residuals are small and randomly scattered in the plot. If there is a pattern, this may suggest that additional terms need to be added to the response surface equations to ensure adequate fit.

- A final check for goodness of fit is performed by running validation cases. Random values of the input variables are selected within the given ranges of input variables used in the design of experiments. These random values are entered into the analysis code, and the results are compared with the results predicted from the response surface equations. Random case validation is the best way to ensure that the response surface equations represent the physics-based analysis to the desired level of accuracy.
- System drivers, trends, and optima are examined by use of Pareto profiles, prediction profiles, and other tools. The computationally efficient nature of response surface equations facilitates the inclusion of uncertainty into the analyses, which would be prohibitive due to the intensive computational demands required by probabilistic analysis.

MOTIVATION FOR DEVELOPING TOAD

TOAD is being developed by the Georgia Tech Aerospace Systems Design Laboratory in conjunction with the Naval Undersea Warfare Center (NUWC). TOAD was created to fill the need for a parametric sizing and synthesis tool and a computational framework for the modeling of torpedoes. TOAD decomposes the sections of a torpedo in the code in a logical fashion analogous to the actual functional sections of a torpedo. TOAD is structured to allow the engineer to easily investigate multiple design cases in a batch format using a single input file. The input method is a generalized method to allow for a high degree of flexibility. TOAD provides a framework for design whereby the various modules of the program can be readily replaced, or upgraded, to produce analytical modules of higher fidelity. This allows for the generic torpedo model to be tailored to the individual needs of the designer in the course of performing a parametric study.

DESCRIPTION OF TOAD

CAPABILITIES AND LIMITATIONS

TOAD is an object-oriented conceptual torpedo sizing program written in C++ as a platform to explore torpedo design spaces. It performs calculations on different sections of the torpedo as well as the integrated torpedo system, and features an expandable architecture capable of incorporating higher fidelity models.

Currently, TOAD is capable of analyzing many aspects of a generic torpedo. The propulsion system analysis can accommodate electrical, integrated motor propulsor (IMP), or thermal propulsion systems. The warhead may be analyzed as either a bulk explosive or as a shaped charge. The sensor section may be analyzed as circular planar, spherical, or line types. The energy section can analyze both Stored Chemical Energy Propulsion (SCEPS) and several different battery types for electrically powered torpedoes. TOAD also considers buoyancy, cavitation depth, and aftbody modeling. A recent addition to the code enables a rudimentary analysis of noise levels as well.

TOAD has several limitations, though several of these will be addressed in future versions. Currently the path of the torpedo is always a straight line, with no maneuvering or throttling allowed during the mission analysis. A more sophisticated noise model is also required to realistically compare different types of torpedoes.

The inputs required by TOAD vary depending on the type of torpedo being modeled. Typically, TOAD will take inputs such as the outer diameter of the torpedo, depth, sensor length, buoyancy length, warhead charge, energy length, energy effectiveness, and motor horsepower. It will then return the length and weight of the torpedo and of the various subsystems, inner diameter, velocity, range, and noise. These inputs and outputs are typical for an electrically powered torpedo, while other forms of propulsion necessitate different sets of data for their particular needs.

ALGORITHMS

TOAD operates using an intuitive object-oriented algorithm for the torpedo sizing process. A simplified schematic of this procedure is shown in Figure 2. For each run, it executes the following steps:

1. Create a torpedo object: TOAD creates a blank torpedo object with no sections in place. This blank torpedo is defined by diameter and maximum depth as well as range and velocity goals. The output type, to the screen or a text file, is also set at this time.

2. Add section objects: Functional sections that comprise a torpedo are defined. Each section is defined as a specific class depending on what type of torpedo is desired by the user. Each section is always placed into the torpedo, however if a section is not needed, it is built into the torpedo using an empty section class. This allows the code to remain object-oriented.
3. Determine torpedo type: TOAD checks the propulsion type to determine if it is an IMP, SCEPS, or electrically powered torpedo, and determines the correct sizing technique based on the specified propulsion system.
4. Preliminary analysis: The necessary functions for the chosen propulsion type are called.
5. Size the torpedo until convergence: TOAD sizes the torpedo until tolerances within the calculation loops for length and weight are satisfied.
6. Performance analysis (velocity, range, noise, etc.): TOAD outputs the performance characteristics of the torpedo to either the screen or a text file.

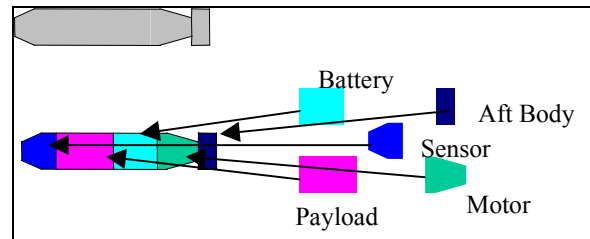


Figure 2: General Sizing Algorithm

FUTURE ENHANCEMENTS

Future enhancements envisioned for TOAD include maneuvering and throttling capability, a better noise model, a more sophisticated battery module, an enhanced drag module, enhanced usability features, and incorporation of advanced multidisciplinary optimization techniques into the sizing process. Also, TOAD was developed using Microsoft Visual C++ and is not cross-platform capable at this time. Future enhancements may include a Linux/Unix port.

IMPLEMENTATION

ELECTRIC TORPEDO

Electrically powered torpedoes have been in existence for quite some time, and have been the weapon of choice for mission scenarios where stealth and low noise are priorities. Generally they have two speeds.¹

An example of an electrically powered torpedo is the Mk-44 produced by the United States, and still in active use by other navies, though it has been retired from active service in the US. However, electrically powered torpedoes are limited in top speed due to constraints on the energy density available from a battery array that must fit within the confines of the torpedo shell. Figure 3 schematically represents the sizing algorithm for electrical torpedoes used in TOAD.

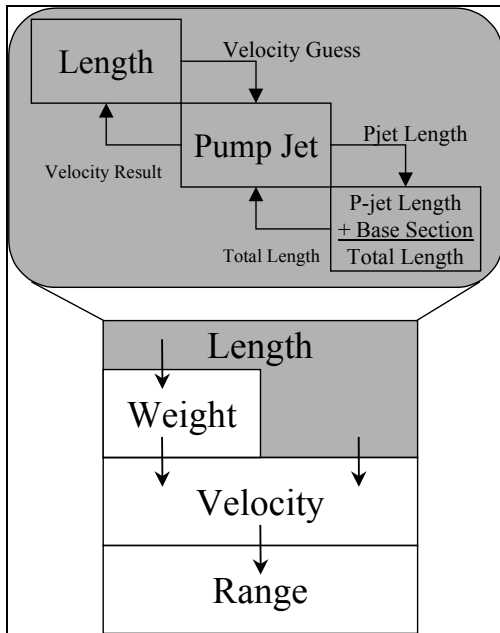


Figure 3: Electrical Torpedo Sizing Procedure

Weight is calculated as a function of length. Velocity is then calculated as a function of length and weight, and range is calculated as a function of velocity and energy. The length is calculated using a loop within a loop.

The base length of the torpedo includes all sections except the pumpjet section and remains constant once calculated and is called the base length. The pumpjet length, which is a function of the torpedo's maximum velocity must be determined. An initial velocity is guessed using the base length as the length of the torpedo. From this guessed velocity, a pumpjet length is calculated. The pumpjet length and base section length are then added together to yield total length, which is then used for calculating a new pump jet length. The total length is compared to the base section plus the new pumpjet length, and this inner iteration is continued until the total length equals the base section plus the pumpjet length.

The outer iteration will continue intelligently guessing velocities until the inner iteration is completed on the first try, where for a guessed velocity, the initial total

length is equal to the base section plus the newly calculated pump jet length. At that point, the sizing process is complete. Figure 4 illustrates a generic electrically powered torpedo as well as the sizing length terms.

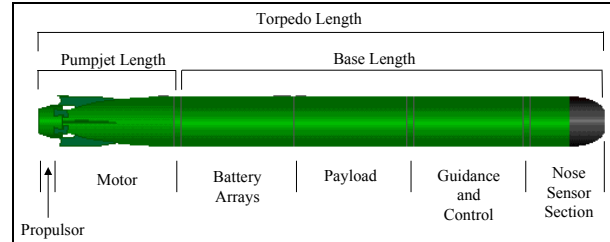


Figure 4: Generic Electrically Powered Torpedo

SCEPS TORPEDO

The Stored Chemical Energy Propulsion System (SCEPS) was developed by the Applied Research Laboratory (ARL) at Pennsylvania State University. A SCEPS engine built by Garrett Pneumatic Systems Division of Phoenix, Arizona powers the Mk-50 Advanced Lightweight Torpedo (ALWT).² Figure 5 shows a schematic of the Mk-50 Advanced Lightweight Torpedo (ALWT), which is powered by a SCEPS motor.

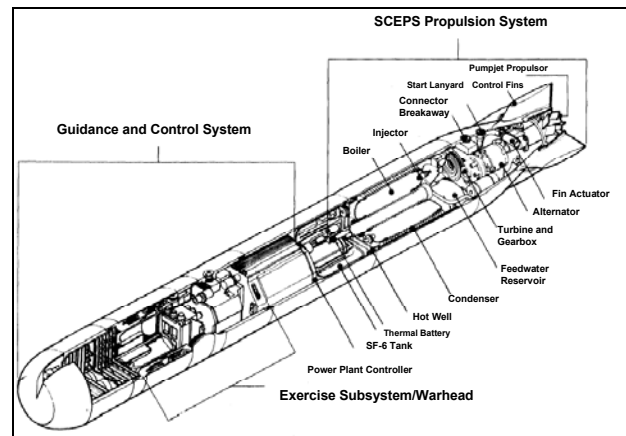


Figure 5: SCEPS Powered Mk-50 ALWT³

SCEPS is a closed-cycle thermal propulsion system developed to be able to engage the new Soviet submarines in the 1980's that could dive to greater depths and threatened to outdo electrically powered torpedoes. SCEPS uses heat generated by the violent reaction of molten lithium and gaseous sulfur hexafluoride to drive a Rankine cycle. This provides power to the propulsor via a gearbox system, and an alternator is used to provide power to sensors and electrical accessories. The heat generated by the reaction within the boiler causes the water contained in

the coils nearby to evaporate and become steam. The steam is used to drive a turbine, and then is cooled in a hull condenser located in the skin of the torpedo, from where it recirculates through the system. A regenerator is used to preheat the feed water to the boiler using heat from the turbine exhaust steam. This eases the thermal loads on both the boiler and condenser.⁴

SCEPS provides several important advantages. Since the cycle is closed, the torpedo's operating performance is independent of depth and there is no external exhaust. SCEPS also has more energy density than is typical of open cycle engines. There are, however, issues with quick acceleration or deceleration, due to residual boiler heat.⁵

The portions of TOAD that analyze SCEPS powered torpedoes are adapted from subroutines within the Torpedo Expert Configuration Analysis Program (TECAP). The original SCEPS and pumpjet sizing routines within TECAP were created by ARL at Penn State. These subroutines were ported to C++ and are implemented by objects that allow them to interface with the rest of the program. Figure 6 shows a schematic representation of the SCEPS sizing algorithm used by TOAD.

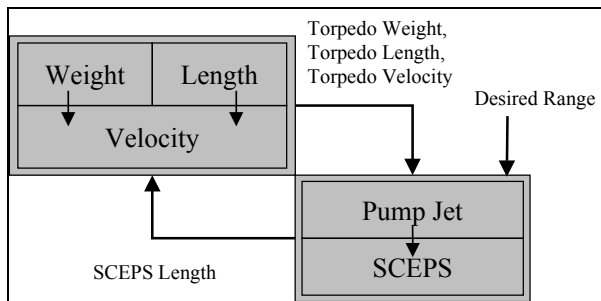


Figure 6: SCEPS Sizing Procedure

Currently, TOAD's SCEPS sizing module accepts thirteen input variables for SCEPS powered torpedoes: turbine inlet temperature, turbine efficiency, regenerator presence, torpedo length, torpedo range, cavitation free depth, crush depth, torpedo velocity, outer diameter, aft body diameter, propulsor weight, propulsor length, and propulsor power. Using these variables, TOAD sizes the SCEPS section of the torpedo accordingly and returns weight, length, and thickness of key components of the SCEPS, as well as power produced.

As can be seen in Figure 6, the SCEPS sizing procedure differs slightly from the one used for an electric torpedo. In the sizing of an electrically powered torpedo, range is an output, but the SCEPS sizing process requires range to be input.

To size a SCEPS torpedo, TOAD calculates torpedo weight, length, and velocity. These calculated values are passed in conjunction with range to the pumpjet and SCEPS sizing objects. These objects return a SCEPS section length to the beginning of the iteration loop, where new values are calculated for torpedo weight, length, and velocity. The sizing loop is repeated until the torpedo length fails to change by more than 0.00001 inches or the maximum number of iterations allowed for the sizing loop is reached, at which point the sizing procedure is complete.

RESPONSE SURFACE EQUATIONS FOR SCEPS POWERED TORPEDOES

The main focus of this paper is to use the newly acquired SCEPS sizing capability in TOAD to illustrate how the design methods used by ASDL can be used to efficiently explore the design space for torpedoes and compare candidate designs. This process will be accomplished by using the SCEPS capability in TOAD to generate response surface equations for responses of interest. Using these response surface equations, candidate torpedo designs can be generated quickly and accurately for comparison with designs derived from response surface equations for the other propulsion systems.

To illustrate the method, the design variables for engine horsepower, outer diameter, fuel heating value, and range were selected for preliminary investigation.

The statistical package JMP 4.0 was used in the creation of the design of experiments and response surface equations. JMP was also used to explore the design space and analyze the results of the experimental runs.

SCREENING TEST

A central composite design of experiments with twenty-five runs was constructed using JMP to perform a screening test. Twenty-five runs were necessary for a central composite design of experiments with two center points. The selected output responses from TOAD were total length, initial weight at launch, buoyancy, SCEPS section length, SCEPS section weight, maximum velocity, and noise. The screening test revealed that each of the selected input variables had a significant effect on the variability of the responses, and these four input variables were carried forward for the next step, the exploration of the design space.

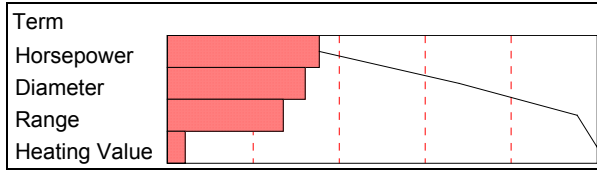


Figure 7: Pareto Chart of Input Variables

An example Pareto chart for the total length response is shown in Figure 7.

EXPLORATION OF THE DESIGN SPACE

For the design space exploration, the input variables were set to the following ranges shown in Table 1.

Table 1: Input Variable Ranges

Input Variable	Lower Limit	Upper Limit
Horsepower	100	300
Diameter	8	21
Heating Value	25650	31350
Range	5	20

JMP was used to fit response surface equations to the outputs from TOAD. Goodness of fit was evaluated by checking the actual versus predicted plots and residual versus predicted plots for each response. Examples of each type of chart for the initial weight at launch response are shown in Figure 8 and Figure 9.

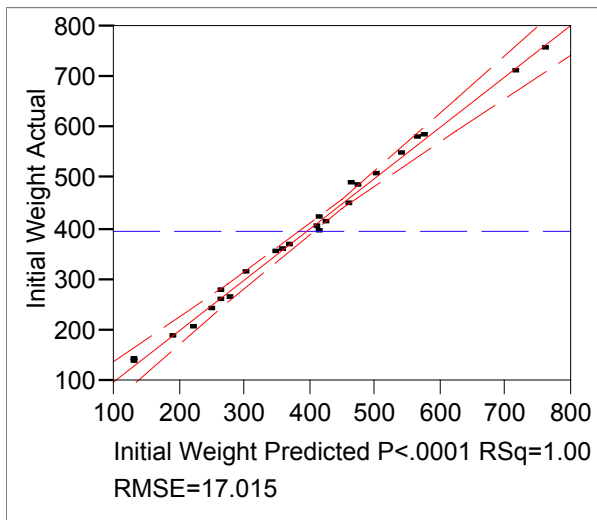


Figure 8: Actual vs. Predicted Plot for Initial Launch Weight

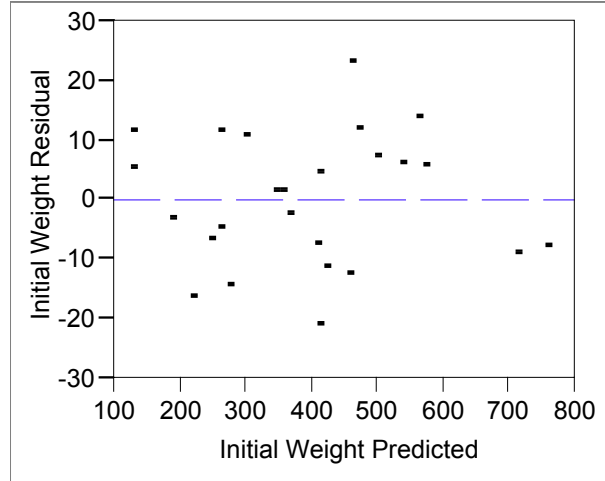


Figure 9: Residual vs. Predicted Plot for Initial Launch Weight

Next, goodness of fit of the response surface equations was further evaluated by running random validation cases. Random values within the ranges for the input variables were generated via Excel’s random number generator, and one hundred cases were run with TOAD using these random values. The responses from TOAD for these random cases were then compared with the values of the responses predicted by the response surface equations, and a percent error was obtained for each of the one hundred experimental runs. Average percent error for each response is shown in Table 2.

Table 2: Average Percent Error for Responses

Response	Percent Error
Total Length	-1.72
Initial Weight at Launch	-0.72
Buoyancy	0.24
SCEPS Length	-2.05
SCEPS Weight	-0.96
Max Velocity	0.33
Noise	0.02

Figure 10 shows plots of the actual values of the random cases from TOAD against the predicted values from the response surface equations for the responses of total weight and SCEPS weight. From observing these charts and the average percent errors for each response, it was concluded that the response surface equations adequately fit the data.

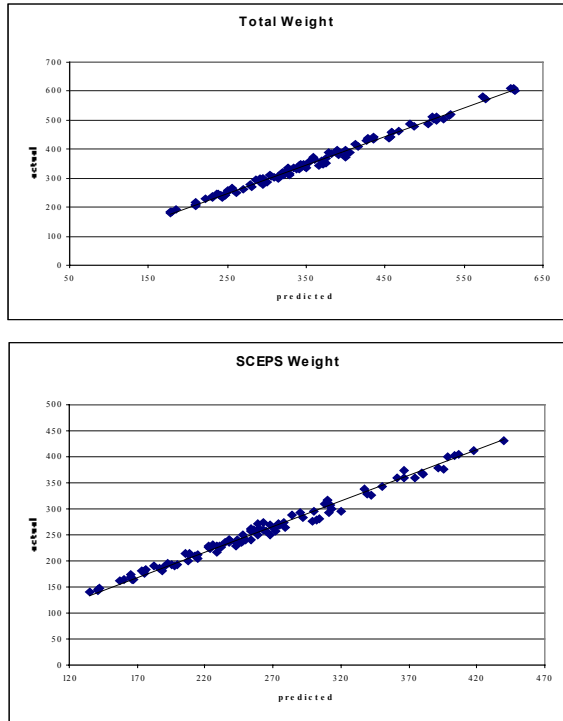


Figure 10: Actual versus Predicted Plot of Total Weight and SCEPS Weight for 100 Random Cases

Once the response surface equations were validated, trends and drivers were analyzed. Figure 11 shows Pareto profiles for the responses for total vehicle weight and SCEPS component weight.

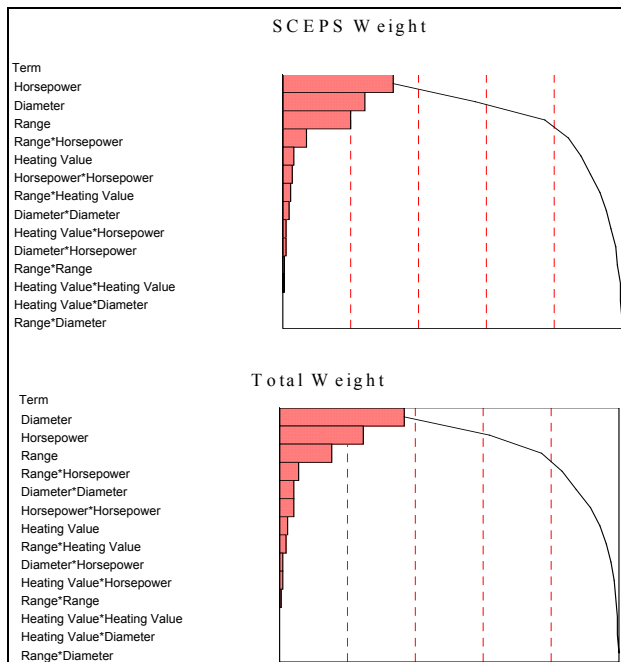


Figure 11: Pareto Profiles for SCEPS Weight and Total Weight

The Pareto profiles in Figure 11 are representative of those for diameter and the other responses. These profiles reveal the principle driving factors.

JMP was used to generate a prediction profiler using the response surface equations generated for SCEPS. The prediction profiler for the SCEPS response surface equations is shown below in Figure 12. The trend lines shown represent partial derivatives. They display the behavior of a response with only one input variable changing at a time. Input variables are listed across the bottom, and responses are shown along the left side of the profiler. These trend lines allow simple visualization of how each response is affected by changes in the input variables. For example, when the value of the input variable for horsepower is increased, the response value for noise increases as seen in the lower left corner of the profiler. The prediction profiler allows the values of the input variables to be varied by moving the vertical dashed lines or by explicitly entering input variable values for investigation. This allows the designer to check if the behavior of the responses makes intuitive sense. If a response fails to behave as expected, it may require further investigation.

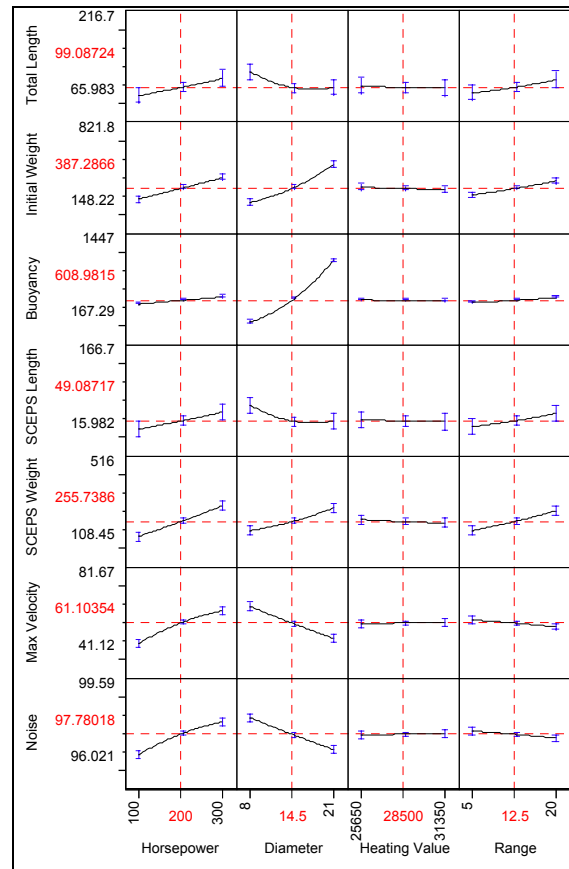


Figure 12: Prediction Profiler for SCEPS Response Surface Equations

The bars at the end of the trend lines shown on the prediction profiler are error bars. If the error bars are small, then the confidence in the trend is high. If the error bars are larger, this signifies that the trend line can be anywhere within the error bars, and confidence is lower for the trend. For the total length and SCEPS length responses, the confidence in the trend is lower, though the average percent error for the response surface equations was still fairly low. This occurred when the ranges for the input variables were expanded to their current limit values. For smaller ranges, the error bars were much smaller.

JMP also includes a contour profiler feature, shown in Figure 13. The contour profiler allows the designer to easily visualize the design space by interactively changing and working with constraints on the responses. Limits can be placed on certain responses, such as length or weight of the torpedo, and the design space is updated in real time as the designer modifies these constraints.

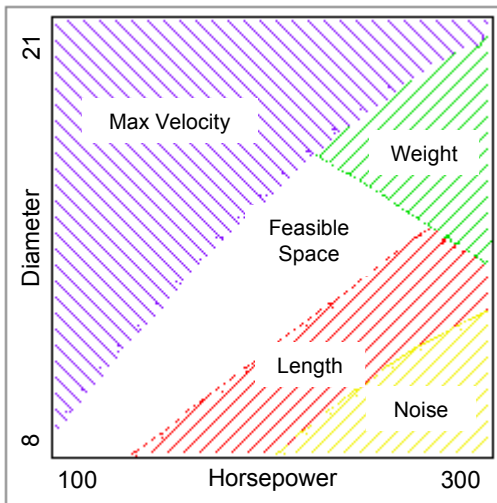


Figure 13: Contour Plots for SCEPS

In the contour plot shown above, the feasible area of possible diameter and horsepower combinations is shown as the unmarked area. The boundaries of the shaded areas denote constraints. Similar plots may be constructed by selecting other input variables for the axes.

RESPONSE SURFACE EQUATIONS FOR ELECTRICALLY POWERED TORPEDOES

Response surface equations for length, weight, buoyancy, velocity, range, and noise were obtained for electrically powered torpedoes during the course of a previous study, and were found to exhibit good fit characteristics. The main thrust of the current study

was to apply ASDL methods to the study of SCEPS powered torpedoes and to use the electrical response surface equations as a basis for comparison when possible. For this reason, more attention is paid to the treatment of SCEPS-based systems than to the electrical ones.

COMPARISON OF SCEPS AND ELECTRICAL TORPEDOES

Response surface equations allow for efficient design comparisons between systems. The following paragraphs illustrate how candidate designs for electric and SCEPS torpedoes were generated and compared using the response surface equations derived from TOAD.

Using the response surface equations generated for both types of torpedoes, velocity versus torpedo length plots were generated as a basis for comparison. These plots are shown in Figure 14.

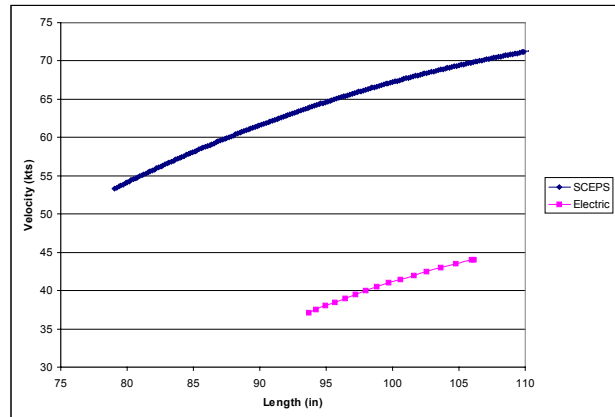


Figure 14: Velocity vs. Length Comparison Plots

The plots shown above were generated by fixing torpedo diameter at 12.77 inches and range at 8 nautical miles. For the electric plot, range is an output, and was held constant by using the solver included with Excel.

The comparison plots illustrate the fact that a SCEPS torpedo of given diameter and length will have a substantially higher velocity than an electric torpedo of the same dimensions, as the two propulsion systems are radically different technologically.

COMPARISONS BETWEEN SCEPS TORPEDOES

Within the SCEPS subsection of TOAD is a cycle subroutine that contains thermodynamic parameters for the sizing of various sub-components of the SCEPS propulsion system, i.e., boiler, feed water pump,

condenser, etc. This cycle subroutine contained a virtual database of thermodynamic parameters that were dependent on the turbine inlet temperature and turbine efficiency of the SCEPS engine, as well as whether or not the torpedo was equipped with a regenerator. The turbine inlet temperatures existed in the database in four sub-sections: 1600, 1500, 1300 and 1000 degrees Fahrenheit. For each temperature heading, there were four turbine efficiency values: 75, 70, 65, and 60 percent. For each one of these temperature and efficiency groupings, there were conditions for a regenerator being present or absent. This yielded a total of thirty-two possible combinations to determine cycle parameters. It was decided for the sake of time to confine the investigation to torpedoes that are equipped with generators, as it would make little sense to omit a generator from the engine, and SCEPS systems are usually equipped with them. This lowered the possible number of combinations to sixteen. In the original Fortran code, the temperature, efficiency, and regenerator values were hard-coded so that when the cycle subroutine was called, it was never asked for any set of thermodynamic data except that pertaining to a turbine inlet temperature of 1600, a turbine efficiency of 75 percent, and a regenerator being present.

TOAD was modified for these three parameters to be treated as input variables, thereby enabling access to a greater set of possibilities for the design space. Since these parameters were discrete, and response surface methodology required that there be a continuous space between upper and lower input variable limits, it was apparent that sixteen sets of response surface equations would be required in order to compare torpedoes of differing turbine inlet temperatures and turbine efficiencies.

COMPARISON OF THERMODYNAMIC CONDITIONS

Early in the study, a comparison between SCEPS torpedoes powered by engines of differing thermodynamic characteristics was performed. The ranges chosen for this section were more limited, thus yielding response surface equations with better fits.

REFERENCES

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- ² Louis C. Gerken. Torpedo Technology. American Scientific Corp. 1989. Page 232.
- ³ United States General Accounting Office. Torpedo Procurement: Issues Related to the Navy's MK-50

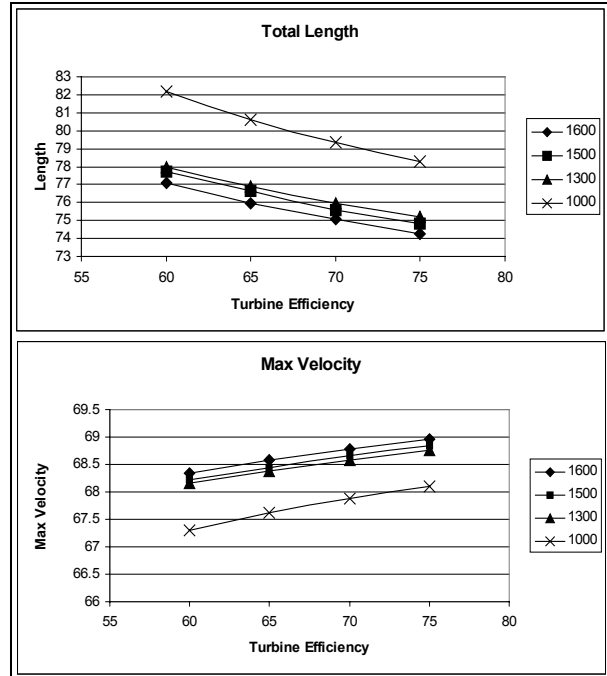


Figure 15: Trends of Total Length and Velocity as a Function of Turbine Efficiency

The trends seemed to indicate that a higher turbine inlet temperature and higher turbine efficiency yielded the best performance for the least weight penalty. As a result, the decision was made to use a SCEPS engine with turbine inlet temperature of 1600 degrees Fahrenheit, and a turbine efficiency of 75% for the comparison between electric and SCEPS torpedoes.

CONCLUSION

This study demonstrated that response surface methodology could be used to accurately model the new thermal analysis capability incorporated into TOAD. The response surface equations allow for fast and simple comparison of different propulsion systems, as well as comparison between systems of the same type but of different parameters. This enables the designer to easily perform studies in order to investigate tradeoffs between systems.

Torpedo Propulsion System. GAO/NSIAD-89-8 January 1989. Page 3.

⁴ Naval Underwater Systems Center. Torpedo Expert Configuration Analysis Program. 1987. Page 43.

⁵ Louis C. Gerken. Torpedo Technology. American Scientific Corp. 1989. Page 232.