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Abstract

Designing a hypersonic vehicle is a complicated process due to the multi-disciplinary synergy that is required. The greatest challenge involves propulsion-airframe integration. In the past, a two-dimensional flowpath was generated based on the engine performance required for a proposed mission. A three-dimensional CAD geometry was produced from the two-dimensional flowpath for aerodynamic analysis, structural design, and packaging. The aerodynamics, engine performance, and mass properties are inputs to the vehicle performance tool to determine if the mission goals were met. If the mission goals were not met, then a flowpath and vehicle redesign would begin. This design process might have to be performed several times to produce a "closed" vehicle. This paper will describe an attempt to design a hypersonic cruise vehicle propulsion flowpath using a Design of Experiments method to reduce the resources necessary to produce a conceptual design with fewer iterations of the design cycle. These methods also allow for more flexible mission analysis and incorporation of additional design constraints at any point. A design system was developed using an object-based software package that would quickly generate each flowpath in the study given the values of the geometric independent variables. These flowpath geometries were put into a hypersonic propulsion code and the engine performance was generated. The propulsion results were loaded into statistical software to produce regression equations that were combined with an aerodynamic database to optimize the flowpath at the vehicle performance level. For this example, the design process was executed twice. The first pass was a cursory look at the independent variables selected to determine which variables are the most important and to test all of the inputs to the optimization process. The second cycle is a more in-depth study with more cases and higher order equations representing the design space.

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Introduction

Historically, the conceptual design of hypersonic airbreathing vehicles, Figure 1, has been performed in a manner much like traditional subsonic/supersonic aircraft design. The design problem has been decomposed into technical disciplines such as configuration, propulsion, structures, airframe aerodynamics, vehicle performance, etc., where the integration is performed implicitly through system level requirements. Individual discipline teams performed their tasks using the methods, solution approach, and technical assumptions of their choosing in order to satisfy the system level requirements, independent of the other disciplines. This practice is acceptable for traditional aircraft design primarily for two reasons. First, most of the interdisciplinary couplings are either not very significant, or can usually be treated as linear. Second, many rapid design/analysis tools exist for these applications, allowing the entire design process to be iterated in a timely manner in order to capture the discipline interactions.

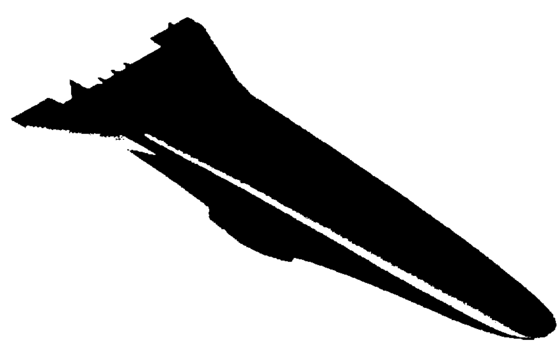

Figure 1: Generic Hypersonic Vehicle

Hypersonic airbreathing vehicle design, however, is dominated by strong nonlinear interdisciplinary couplings and interactions, requiring a much more tightly integrated design process which does not readily lend itself to discipline decomposition. For example, the hypersonic vehicle flowpath (propulsion) is essentially the entire lower surface of the vehicle (aerodynamics). Furthermore, due to the higher level of sensitivities, higher fidelity methods are required at the conceptual design level in order to sufficiently resolve hypersonic designs. To improve the conceptual design process it is desirable to have a method which allows for rapid analysis of a large design space while maintaining the fidelity and multi-disciplinary interactions required for hypersonic vehicle conceptual design.

An approach is being developed using a Design of Experiments (DOE)[1,2] method to meet the design requirements. This paper will discuss the design cycle, the tools developed, and an example which illustrates the necessary steps. Although the process is becoming more automated, these studies are not meant to remove the engineer from the process, but to use the engineer's time more wisely and provide a powerful design tool. The methods presented here have greatly reduced the time necessary to produce the geometry needed for a flowpath study. In the future, the team would like to extend the DOE methods to other disciplines and develop software to improve the team's ability to develop designs in a more synergistic fashion.

Since hypersonic vehicles are viewed as a enabling technology in both military and space access applications, the specifics of the engine flowpaths of any meaningful vehicles are restricted to the U.S. government and its contractors. In order to show an example of this design process, an unclassified example of engine geometry and mission has been generated. The mission for this study was a Mach 7 cruise, and the vehicle flight was assumed to begin on condition. The objective of the example design study was to maximize the cruise range for the fixed amount of fuel volume available in the "as drawn" vehicle. This study is to be viewed only as an example, and the results should not be used to describe the performance of any real cruise vehicle.

Design of Experiments

Designing a hypersonic airbreathing engine is a complicated process. The DOE process was chosen for the conceptual flowpath design because a large number of independent variables could be investigated without having to run every perturbation of the variables. It also provides the flexibility to add constraints or modify the design mission. The DOE method uses statistical techniques to build polynomial approximation models for the functional relationships between output responses (engine performance characteristics) and input design variables (flowpath geometry and flight conditions). The parametric model is then used to determine the effect of design variables on the output responses and to predict the best design variable values to optimize the performance characteristics. It is also assumed that the fitted surface is an adequate representation of the true response function. The results from such studies need to be review by each discipline to make sure that no design issues exist.

Design Process

In the past, a propulsion engineer would design a flowpath by optimizing engine performance like thrust or specific impulse for several Mach numbers. Next, a vehicle designer would build a vehicle around the flowpath and pass the design on to the various disciplines such as aerodynamics and structures. Databases of propulsion and aerodynamics and a mass properties model would be loaded into the trajectory optimization code. This approach may require several iterations in order to meet all of the mission requirements without violating any constraints developed by each discipline. It is proposed that if the flowpath could be designed taking into account vehicle effects such as aerodynamic forces, the design process could require fewer iterations. Figure 2 represents the design process that has been developed to consider contraints from each discipline while the flowpath is being optimized for the specific mission. Each block of the process will be discussed in greater detail.

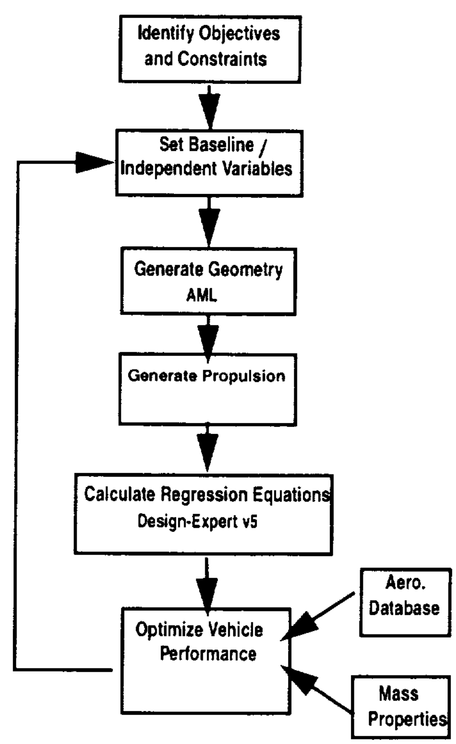

Figure 2: Conceptual Design Process

Objectives/Constraints

Defining the objectives means understanding the mission and how the engine will have to operate to accomplish the mission. Along with goals associated with the mission, there have to be ground rules set by disciplines so that in varying the design to meet the mission, unreasonable results that affect other disciplines do not occur. Usually, these constraints cannot be fully specified in the beginning. This is one reason why DOE's are used in these studies. If enough output responses are included at the beginning of the process, contraints that arise during the study can be addressed by an equation that already exits. Currently, there are 43 responses that are bookkept in the design process. In most designs, all of the responses are not used, but they are available if needed.

Baseline/Independent Variables

First a baseline geometry is generated. This can come from an existing flowpath if the goal of the study is to improve an engine or it can be generated. The baseline must include all of the design relationships that will be used in the study such as minimum cowl thicknesses, included angles, etc. Choosing the independent variables is how the design space is covered. The baseline is tied into this because the baseline geometry needs to include all of the geometry pieces that will be varied in the study. The vehicle flight conditions that will be needed in the trajectory optimization need to also be included as independent variables. The range of the independent variables is important because the range affects which parameters have the most influence on the output responses.

Geometry Matrix Generation

The matrix of engine geometries is generated by objects written in the Adaptive Modeling Language (AML). AML provides a knowledge-based engineering (KBE) framework that allows the modeling and capturing of knowledge from different domains. This functionality is achieved using an object-oriented architecture. The AML modeling framework consists of several modules representing different knowledge domains. All the modules are written with the AML object-oriented architecture although they can communicate with external programs through the Virtual Layer architecture. Additional modules can be defined and loaded into AML to "adapt" the language for a specific purpose.

The AML geometry generator which is used for these studies requires three inputs. First, the geometry baseline is loaded as a template. Next, a file is loaded which supplies the three values (minimum, mean, and maximum) of the independent variables. Next the experiment layout is added. This is a file that is generated by the statistical software and contains the coded values (-1, 0, +1) of each independent variable for each case that will be run in the study. Figure 3 shows the AML interface with a geometry template loaded and ready to begin to generate the DOE matrix of geometries. The resulting geometry is written to a file that can be directly pasted into the hypersonic propulsion code.

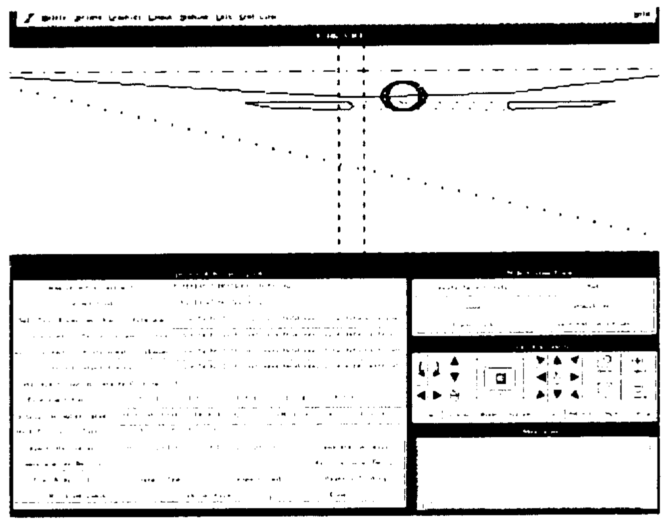

Figure 3: AML Interface

Propulsion Performance Generation

The propulsion code used in this design process is a tip-to-tail hypersonic cycle analysis tool. The code was developed at NASA Langley Research Center and uses a two-dimensional Euler method for the forebody/inlet and nozzle and a one-dimensional incremental combustor with an integral boundary layer method for all components. The pertinent output responses are tabulated and pasted directly into the statistical software.

Regression Equations

The Design Expert[3] software uses statistical methods to generate the regression equations for the various propulsion output responses. The software has many options for experiment designs. For a screening analysis[4], a two-level factorial design is used. This produces linear equations where the main effects are aliased with several other interactions. These equations are not meant to fully represent the design space. These equations are only meant to determine which of the independent variables are the most important and to verify that the design process is working correctly. To develop higher order equations to more accurately represent the design space, a central composite design (CCD) is used. This method can yield quadratic or cubic equations and reduces the amount of aliasing involved to interactions that should not be important in the responses. For either the screening matrix or the CCD matrix, the Design Expert software generates the equations to be fed into the vehicle trajectory optimization code which will also optimize the flowpath in these studies.

Vehicle Performance Optimization

Mass Properties

As mentioned previously, the trajectory code requires aerodynamic, propulsion, and mass properties databases to operate. Initially for a study, the weight and center of gravity will be only an estimate. As the design matures, the fidelity in the weight estimate increases. The trajectory optimization code starts with the vehicle weight at the beginning of the mission, and then reduces the weight as the fuel is consumed. A crude packaging of the "as drawn" vehicle has also been done to give a rough estimate of propellant volume, and therefore weight, available to perform the mission.

Aerodynamic Data and Force Accounting

It is very important that the team agrees as to what vehicle surfaces are bookkept within each discipline. Figure 4 shows which surfaces of the vehicle are accounted for by aerodynamics and which are accounted for by propulsion. Obviously, it is very important to bookkeep forces and moments correctly and have well defined boundaries for each discipline. Figure 4 also shows that the propulsion code is being used to predict forces and moments on what are typically aerodynamic surfaces. The propulsion code is being used for the forebody and external cowl forces and moments in these studies since the flowpath geometry is changing enough for each geometry case to greatly affect the results. For speeds greater than Mach 4, engineering codes can produce adequate results for conceptual design with short analysis times. These codes employ impact and shadow methods for inviscid pressure solutions over arbitrary bodies. Reference temperature and reference enthalpy methods are used to calculate viscous effects and Reynold's analogies are used to predict heat transfer data for ideal or real gases.

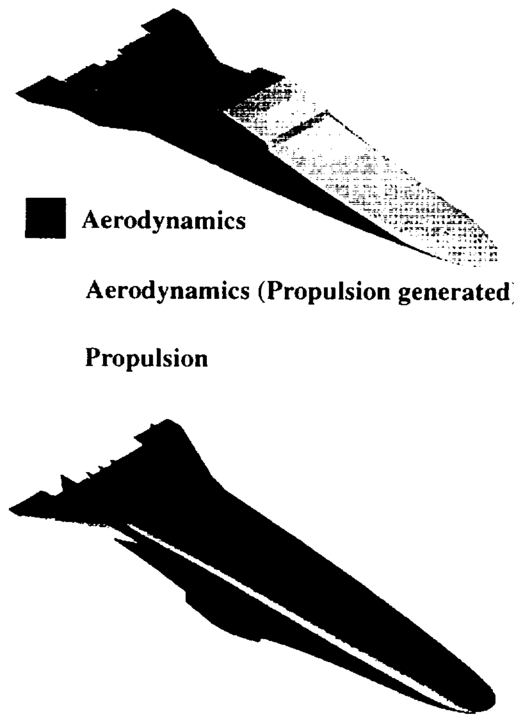

Figure 4: Vehicle Surfaces Force/Moment Accounting

Trajectory and Flowpath Optimization

The trajectory and vehicle optimization are completed using a 3-degree of freedom (3-DOF) code. The goal of the trajectory and flowpath optimization varies with the mission. For a hypersonic vehicle, the mission can vary from a simple cruise to orbit insertion. Figure 5 illustrates the trajectory code inputs and outputs and how the optimization process proceeds. As discussed earlier, aerodynamics, mass properties, and propulsion information is put into the trajectory optimization code as either a databases or as regression equations. General constraints are then applied. Typically, the structural engineer will specify acceleration/load limits; the aerodynamicist and propulsion engineer will specify minimum and maximum operating angles-of-attack for either operability or controllability purposes, etc. Then mission requirements and constraints are applied either as waypoints/trajectory events or as limits on trajectory parameters. The code combines the vehicle data with the trajectory contraints and mission events to produce the vehicle trajectory model. The user then supplies an initial guess of the independent variables, and the optimizer does the rest. Typically, the optimizer will try first to meet all of the constraints, and then proceeds to optimize the overall mission goal (i.e. maximize range, minimize weight, etc.). It should also be mentioned that although each independent variable is allowed to change from iteration to iteration during the optimization, the geometry pieces that would be fixed in a vehicle do not change during the trajectory simulation.

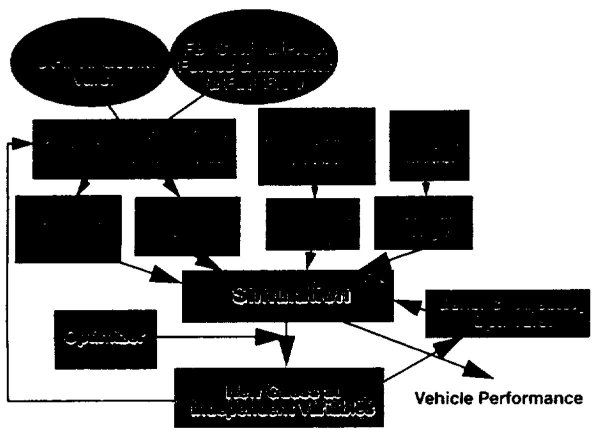

Figure 5: Optimization of Flowpath and Trajectory

Design Process Example

To illustrate the design process, a simple example study was conducted. The mission objective was to maximize the range of a Mach 7 cruise vehicle for a given fuel volume. The constraints included fixed Mach 7, dynamic pressure 1000psf, and vehicle length. Table 1 defines the independent variables. Five independent variables were used for both the screening matrix and the CCD matrix. The first variable is for the vehicle angle-of-attack (α) which is required to vary in order to maintain the "lift equals weight" cruise trajectory. Figure 6 shows the geometry definition for the study. The forebody consists of a ramp of varying angle (θ) and length (Xs). The only other geometry that was allowed to vary in the study was the engine throat height (Ht). The remaining independent variable was engine fuel equivalence ratio (ϕ). Since this was an example generated only for illustration, the geometry has been greatly simplified. A more realistic study would include 10-15 independent variables.

Table 1: Independent Variables Definition

Independent Variables	Variable Description
α	Vehicle Angle-of-Attack
θ	Forebody Ramp Angle
Xs	Length of Inlet to Shoulder
Ht	Engine Throat Height
ϕ	Engine Fuel Equivalence Ratio

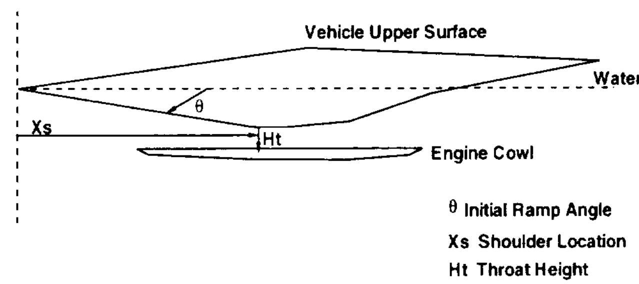

Figure 6: Design Study Geometry

Screening Matrix Discussion/Results

A baseline template and the screening matrix of geometries were generated by AML. A quarter fractional factorial screening matrix for 5 independent variables requires 8 cases to cover the design space. This is a small number of cases which causes the main effects to be aliased with interactions. For example, the main effect of angle-of-attack was aliased with the interaction of ramp angle and throat height and the interaction of the shoulder length and equivalence ratio. The minimum and maximum values (-1 and +1 in coded values) were used for each independent variable in the screening matrix.

The propulsion code was used to generate the responses which were loaded into the statistical software. The method of least squares was employed to fit a first-order regression model to the computed responses. The regression equation was then used to assess the significance of the design variables on the responses and predict the behavior of responses in the design space. Figure 7 is a graphical representation of how well the regression equation for the engine axial force agreed with the actual values generated by the propulsion code. A diagonal line was drawn to show the closeness of the analyzed and model predicted values. The coefficient of determination (R^2) varies from zero to one indicating how closely the regression model fits the original data. The regression is a perfect fit if R^2 equals 1. Notice the R^2 value for the axial force is .961. Usually, inadequacies in the linear curve fits are expected to be improved when a higher order regression equation is generated in the CCD matrix.

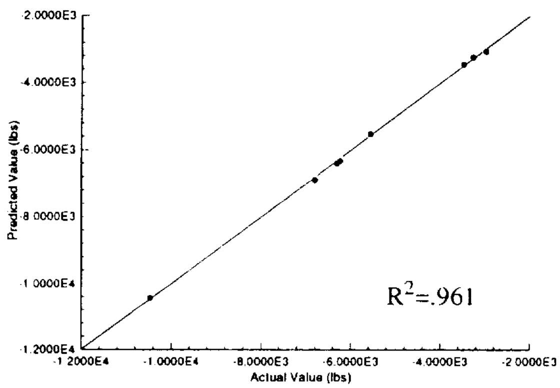

Figure 7: Regression Model for Engine Axial Force

The relative percentage of influence of the regression coefficients on a response can be shown as a Pareto plot[5]. For example, the Pareto plot for engine axial force is shown in Figure 8. Keep in mind that the range of values investigated for each independent variable also affects which variables are most important to each response. The screening matrix really should not include variables that are known to be important such as angle-of-attack. However, this variable was needed to optimize the vehicle trajectory as well as the flowpath.

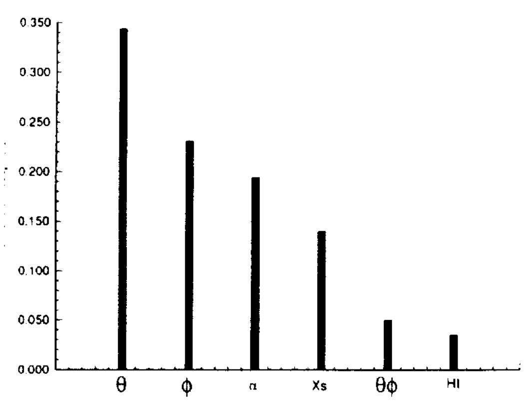

Figure 8: Screening Matrix Pareto Plot

All of the necessary response equations were loaded into the trajectory simulation code. Table 2 shows the optimized coded values for the 3 geometric independent variables that do not vary over the trajectory (meaning there is no variable geometry in the resulting vehicle). Note that each of the 3 variables were pegged to one end of the investigated range. In a relevant design study, the range of the independent variables that were pegged would have been expanded to be sure that the variable would not be pegged in the CCD. The angle-of-attack varies to maintain "lift equal weight" and the equivalence ratio varies to maintain "thrust equal drag" over the trajectory. The optimization process achieved a mission range of 1182 nautical miles. Again, this is an example and does not represent the actual range of any real vehicle.

Table 2: Screening Matrix Optimized Coded Values

Independent Variables	Optimized Coded Value
θ	-1
Xs	-1
Ht	-1

<u>**CCD Matrix Discussion/Results**</u>

In order to generate higher order equations to improve the regression models, a CCD matrix was run. The CCD matrix was a half fractional matrix which produces 2nd order equations. The same baseline and independent variable values were used as in the screening matrix even though some of the independent variables were pegged in the screening matrix. This was done to directly illustrate the differences between the screening and the CCD matrices results. For the CCD matrix, 3 coded values are used for each independent variable (-1, 0, and +1). For 5 independent variables, 27 cases were run in the CCD matrix. The results for the CCD model are shown in Figure 9. The model agrees very well with the cases generated by the propulsion code. Notice that the R^2 value is very high which is expected for a quadratic model.

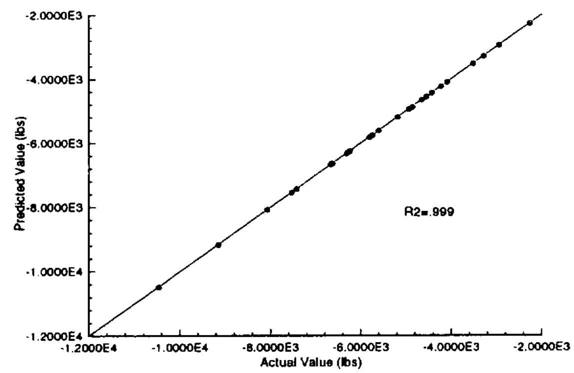

Figure 9: CCD Regression Model for Engine Axial Force

The CCD Pareto plot for the engine axial force is shown in Figure 10. Notice that the first 5 most important coefficients are identical to the screening matrix, but that the throat height is now less important than some interactions. This shows that the more accurate quadratic regression equations do model the design space differently than the linear regression equations from the screening matrix.

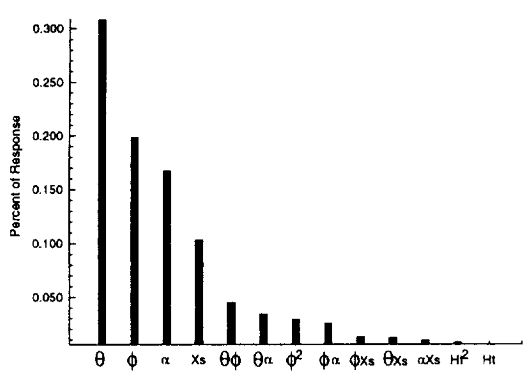

Figure 10: CCD Pareto Plot for Engine Axial Force

Again, the regression equations were loaded into the simulation code so that the flowpath and the vehicle trajectory could be optimized simultaneously. Table 3 shows the optimized coded values for the 3 geometric independent variables that are fixed in the resulting trajectory. The two other independent variables in actual values that do vary during the trajectory are shown in Figure 11. Optimization of the CCD equations resulted in a new mission range of 1539 nautical miles.

Table 3: CCD Matrix Optimized Coded Values

Independent Variables	Optimized Coded Value
θ	-.913
Xs	-.870
Ht	-1.00

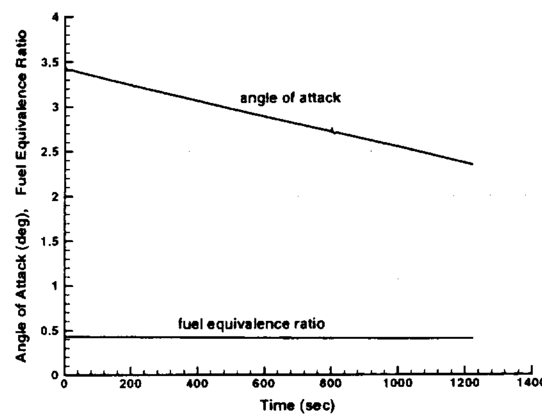

Figure 11: CCD Optimized α and ϕ

Summary and Conclusions

Designing an engine flowpath for a hypersonic vehicle is complicated due to the high degree of engine/vehicle integration. This paper has attempted to describe methods being developed to shorten the design process needed to define a vehicle by optimizing a flowpath while accounting for the other pieces of the vehicle performance. Design of Experiments methods have been used in this design process to minimize the number of propulsion cases needed to describe the design space and produce regression equations that can be used to optimize flowpath geometry while the vehicle trajectory is optimized. These studies are not meant to remove the engineer from the process, but to use the engineer's time more wisely. The methods presented in this paper have greatly reduced the time necessary to produce geometry for flowpath development. In the future, the team would like to extend the DOE methods to other disciplines and develop AML software to improve the team's ability to work together on synergistic designs.

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