ASSESSING ENGINE HOT FIRE DATA FOR HUMAN SPACEFLIGHT APPLICATIONS

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ABSTRACT

Development and certification of liquid engine systems for human spaceflight missions requires exhaustive analysis to meet the NASA's requirements for engine health, reliability, and performance. The techniques used to assess requirement conformance and test-to-test engine health pose many unique challenges including the unusually large scale of data, complex component and system analysis, and rigorous engineering judgement standards. To address these challenges, NASA Marshall Space Flight Center's Engine Systems branch has developed and maintained a robust software suite and operational processes that satisfy programmatic requirements levied on engines and the 7 Elements of Flight Rationale. Analysis at a systems level includes subsystem assessment of components such as turbomachinery and combustion devices as well as structural and fluid dynamics and transient and steady-state assessment at a systems level. Some of the most important tools to accomplish this analysis are automated script databases, creation of historical and statistical comparisons, and parameters calculated at the full data rate. These tools greatly simplify the crucial processes of anomaly investigation, limit monitoring, health assessment, and timely communication of key conclusions drawn from hot fire testing and flight data analysis.

INTRODUCTION

From development and certification to flying with human passengers, a rocket engine's success depends on engineers' ability to analyze and communicate its performance. In developmental engine testing, effective analysis can save critical time and money; in flight programs, it is essential for understanding risks. To establish these capabilities, NASA Marshall Space Flight Center's Engine Systems branch and its predecessors have developed and maintained software solutions tailored to industry needs that are generally available for public use at no cost.

DATA ASSESSMENT FOUNDATIONS

Regardless of the application, data analysis consists of processing and assessing data. Whether one is exploring data or explaining it, human interpretation through visualization is key to effective assessment. WinPlot, a desktop graphical analysis program, provides the capabilities required for both processing and visualizing data. Originally named UCPlots, WinPlot was created in 1994 to fulfill the need for fast and easily managed graphical displays of test article and facility data. It is still the foundation for NASA engine systems data analysis thanks to its continual updates in response to industry needs. WinPlot and many of its companion programs are available for public use through the NASA Software Catalog.

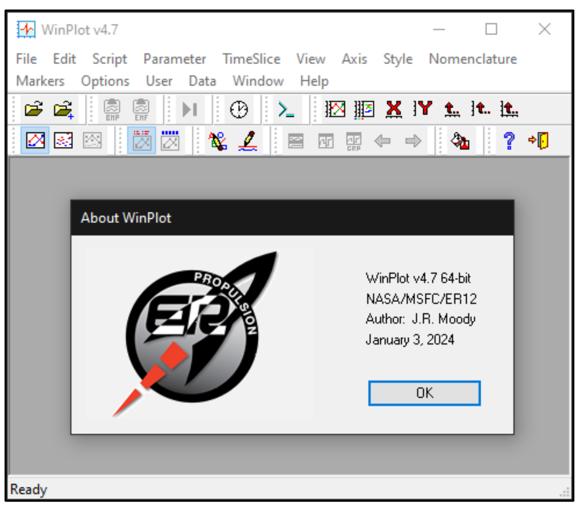

Figure 1. WinPlot User Interface

DATA PROCESSING

One of the biggest challenges in engine data assessment is the data's scale hindering access. Engine tests and flights often record hundreds of parameters for hours at a time. With data coming multiple data acquisition systems at variable rates, uncompressed data is impractical to work with. To solve this issue, WinPlot introduced the Sun binary file format, which compresses and saves measurement data with associated metadata. Common Time and Compressed are the most common versions of Sun files, maximizing data compression and speed of retrieval. These files require all data to be recorded at the same rate; however, they support data dropouts and high-resolution time stamping, allowing accurate timing of individual data points and aligning data from numerous acquisition system. By saving each measurement with unique timestamps, Sun Multi Time files support data with variable sample rates at the cost of slower retrieval and larger files. Data saved as comma separated values is typically 50-100 times larger than its Sun format equivalent.

In addition to data access, engine data processing requires calculation of parameters derived from measurements. By providing mathematical and logical expressions, WinPlot allows users to quickly make simple calculations like converting a measurement from psig to psia and averaging multiple collocated measurements. It also facilitates more complex operations such as automatically correcting sensor bias during hot fire based on data recorded when the sensor's local environment transitioned from gaseous to cryogenic liquid. With WinPlot's pre-defined functions, users can calculate trigonometric and logarithmic values as well as polynomial curve fits and parameters derived from measurements' sample rates and timing.

As reflected in WinPlot's file formats, hot fire data is characteristically temporal, requiring time-alignment for analysis. When analyzing parameters generated during a single hot fire, alignment to an absolute reference, typically Greenwich Mean Time, can be sufficient. However, when assessing data from multiple tests and/or flights, relative time references are required. These time references, or events, often come from engine, vehicle, or ground support commands, but they may also require creation via data processing. EventGen, one of WinPlot's associated programs, allows users to either insert events at explicit times or define logic statements to automatically create events based on data trends.

VISUALIZATION

While data processing is a prerequisite for assessment, an assessment's efficacy is entirely dependent upon humans correctly interpreting the data through visualization. The two primary forms of data visualization are tabular displays of textual information and pictorial displays or plots. Tabular displays provide more precise information, but they do not offer any temporal context. In contrast, illustrative plots are much more information-dense and intuitive.

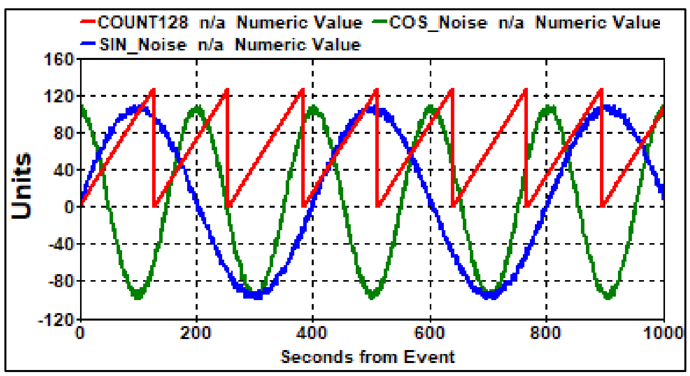

Figure 2. Example Data Review Plot

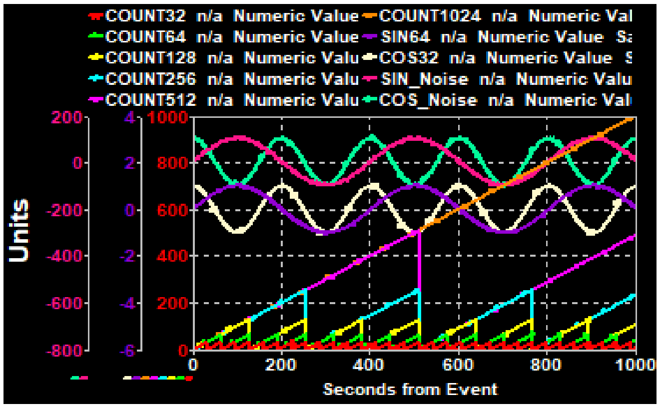

Figure 3. Example Data Assessment Plot

The choices made when creating a plot can be broadly divided into two categories: aesthetic and dimensional. Aesthetic options chiefly distinguish different plotted parameters and depict their nature. Some of the most vital aesthetic choices include plotted data's color, weight, and identifying markers, all of which help to intuitively associate the parameters with the legend and each other. One way color options are often exploited in engine systems applications is by assigning unique colors to individual fluid systems, e.g. green for oxidizer, red for fuel, blue for hydraulics, and yellow for pneumatics. Another common technique is assigning rainbow colors to parameters when their magnitudes are expected to be in a specific order, such as temperature measurements on a cryogenic supply line. These practices allow users to quickly identify and assess anomalies in crowded displays.

The dimensional aspects of data visualization are more important than the aesthetic, determining how the data is spatially displayed. Engine data is typically plotted as a time series, but it is sometimes required to change the horizontal axis parameter to visualize things like target boxes, saturation curves, and turbomachinery performance characteristics. In contrast, vertical axes must be even more dynamic, supporting creation of multiple axes with individual scales and assign parameters to those axes based on chosen criteria such as units, magnitudes, and source files.

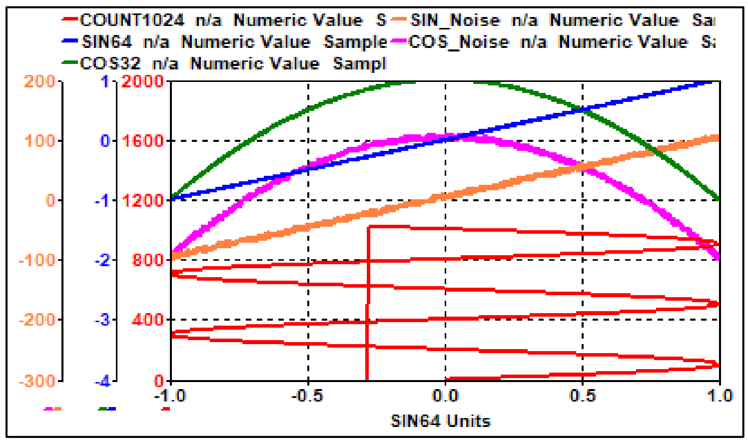

Figure 4. Data Review Plot with Sine Parameter X-Axis

USER INTERACTION

In data assessment, user control of the analysis software can be either passive or active, defining commands prior to accessing data or interacting with data directly. WinPlot meets analysis requirements for passive control with its extensive native scripting language, allowing the user to define a set of chronological commands for the program to execute. Saved in simple text files, scripts can be written from scratch or recorded while interacting with WinPlot. Scripting and manual control both support full user control over WinPlot's processing and visualization capabilities.

In addition to all the data analysis features outlined up to this point, WinPlot scripting enables passive software command in response to events via the Auto Run function. After an event is generated by a change in engine phase/mode or a parameter-based logical expression, WinPlot executes the script associated with the event in an Auto Run assignment. This feature is critical in effective real-time assessment of hot fire data. As an engine proceeds through chill and hot fire, or a rocket through its launch phases, redline limits can vary greatly. To keep up with the changing limits, phase-change events can trigger scripts that add or remove limit markers, parameters of interest, and whole plots.

During real-time and post-hot fire analysis, observations frequently require rapid investigations. WinPlot's lean data structures enable active user interaction with up to 1000 rendered parameters from 1000 data sources simultaneously. Visualizations of unrestrictive amounts of data can be dimensionally and aesthetically manipulated swiftly and intuitively, making WinPlot an indispensable tool for engine systems investigations.

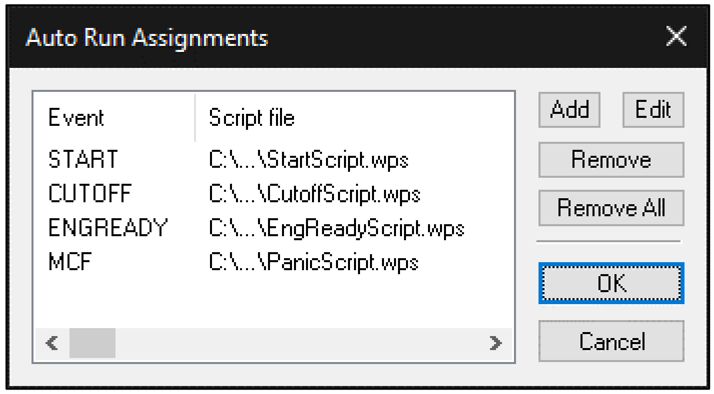

Figure 5. Auto Run Assignments Example

APPLIED DATA ASSESSMENT

Following the Space Shuttle Columbia disaster in 2003, NASA postponed future Space Shuttle flights until its safety culture reflected the values needed for a return to flight. This reevaluation of engineering practices led to development of the Seven Elements of Flight Rationale, a framework for assessing any risks to human spaceflight missions. To both analyze and communicate risks, NASA engineers address each of the Seven Elements as shown in Table 1.

Table 1 – Seven Elements of Flight Rationale

#	Element	Element Expanded
1	Solid technical understanding	Physics-based or root cause understanding of issue, based on engineering data (perhaps using a fault tree)
2	Condition relative to experience base	Experience base includes full-scale flight, ground test, or qualification-level tests
3	Bounding case established	Using physics-based understanding, determine the bounding case
4	Self-limiting aspects	Physical reasons why it can't get any worse than the bounding case or show the part is fail-safe
5	Margins understood	Adequate margins, ideally not substantially reduced from baseline
6	Assessment based on data, testing, and analysis	Final risk assessment based on test data and analysis, not gut feel or expert opinion
7	Interactions with other elements and conditions addressed	Address interactions with other conditions (MRB, changes, technical issues), and vehicle elements

UTILIZING THE EXPERIENCE BASE

In engine systems risk assessment, the second and sixth elements of flight rationale both rely heavily on the assessor's ability to access and make use of pertinent hot fire data. Depending on the situation, relevant hot fire data for comparison and analysis can be found using manual or automated methods, but a combination of both techniques is usually required. WinPlot's built-in Query tool allows users to search datasets of any size for specific conditions in a specified timeframe. Datasets searched

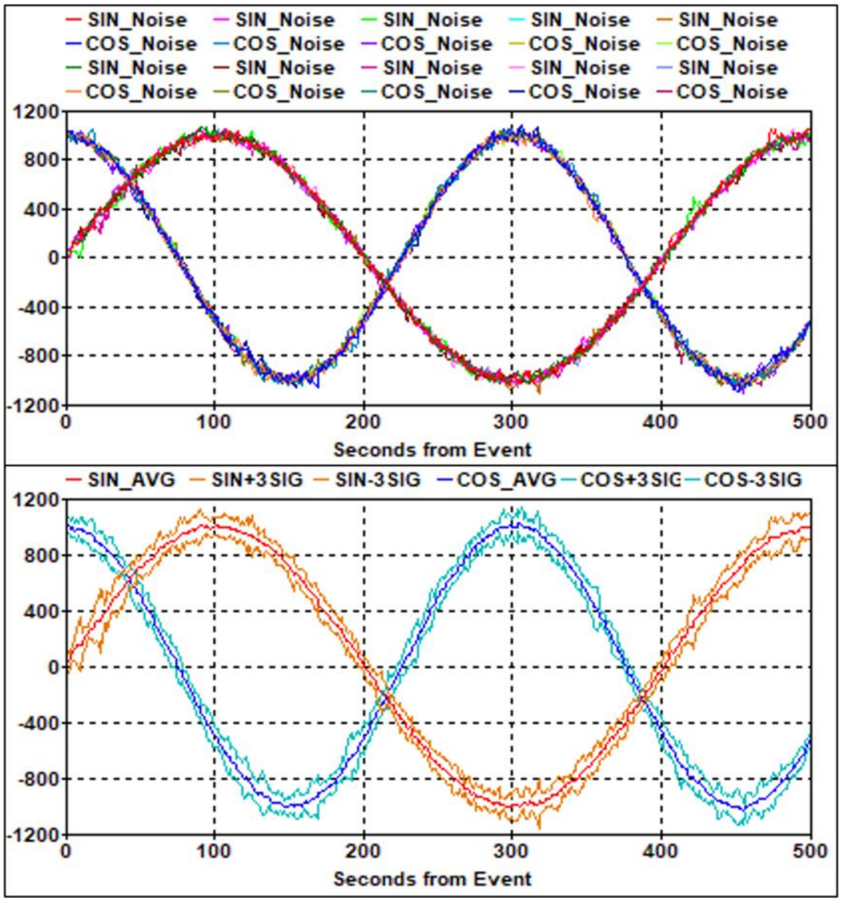

Figure 6. Data Used to Generate Sigmas (Upper) and Generated Sigmas (Lower)

with Query often include over 1000 hot fires, consisting of both tests and flights with 3-10 files each. Query searches output a more manageable dataset that can be opened in WinPlot for manual assessment.

Datasets comprised of 1000 files or fewer are typically saved using database directory files (dbdirs). Database directories are often used to reference all the files from a test, flight, test series, profile type, or engine configuration, allowing users to access suitable comparisons in seconds. Once the data is loaded, the user may select the parameter(s) and time slice of interest to generate statistical information that can be used to quickly identify similar and extreme cases.

Early in an engine's lifecycle, a limited experience base requires data undergoing assessment to be compared directly to the available applicable history. However, once an engine has accrued sufficient consistent tests, more significant comparisons can be made to its statistically consolidated history. Given a dataset, time slice, and choice of parameters, the WinSig program generates a Sun file containing a data series for each parameter's minimum, maximum, average, and standard deviation during the chosen time slice. These "sigma" files are particularly useful when assessing an engine's transient performance since the start and shutdown profiles should not vary significantly under nominal conditions. Data calculated this way is also often delivered for mission design, returning to the engine system as an interface control requirement.

APPLYING TECHNICAL UNDERSTANDING

The first element of flight rationale, solid technical understanding, underpins the subsequent 6 elements and should be validated with analysis using hot fire data. To compensate for measurement systems' limitations, physical principles and models may be assessed using parameters derived from test data.

Most calculations can be performed using a single WinPlot expression, since their only practical limitation is 128 individual input parameters. However, more complex calculations may require intermediary calculated parameters and additional data sources. SunCalc, another WinPlot companion program, can be used for these intricate calculations. Supplied with a Sun file or database directory and text-based set of expressions using WinPlot syntax, SunCalc generates a new "calc" file containing the calculated parameters. In addition to multi-step calculations, SunCalc supports REFPROP expressions, allowing users to calculate the thermodynamic and transport properties of a limited set of fluids and mixtures. These capabilities are regularly used to calculate extensive turbomachinery performance characteristics and unmeasurable values like internal bleed rates with high accuracy.

OPERATIONAL DATA ASSESSMENT

Engine systems data analysis operations in human spaceflight programs can be divided into three categories: real-time support, exploratory assessment, and data review. Each category requires a different form of data assessment. Real-time support requires monitoring as much data as possible to quickly identify anomalies and make decisions. Exploratory assessment includes pre-hot fire risk assessment and post-hot fire health and performance assessment. Data review involves communicating the results of exploratory assessment by presenting the data for stakeholders to assess.

To keep up with progressing schedules, automating script review package creation throughout the analysis process is a necessity. The most widely adopted solution for script automation is a Visual Basic for Applications driven Excel workbook known as the WinPlot Script Database. Versions of this workbook are used by various engine systems and subsystem teams to repeatedly create real-time, post-hot fire, and data review scripts. Many teams also use a PowerPoint add-in to automatically populate presentations with exported plots.

The Python application MultiFile is an alternative to the WinPlot Script Database used by some teams, offering many of the same features and a few more. MultiFile also interprets an Excel workbook to create scripts; however, it incorporates event insertion and review creation for a more consolidated and adaptable process. Using the dynamic-link library SunAcc, applications written in C and Python can read and write Sun files. MultiFile uses this capability to generate review plots without WinPlot then hyperlink the plots to WinPlot scripts that create the same plot for active interaction.

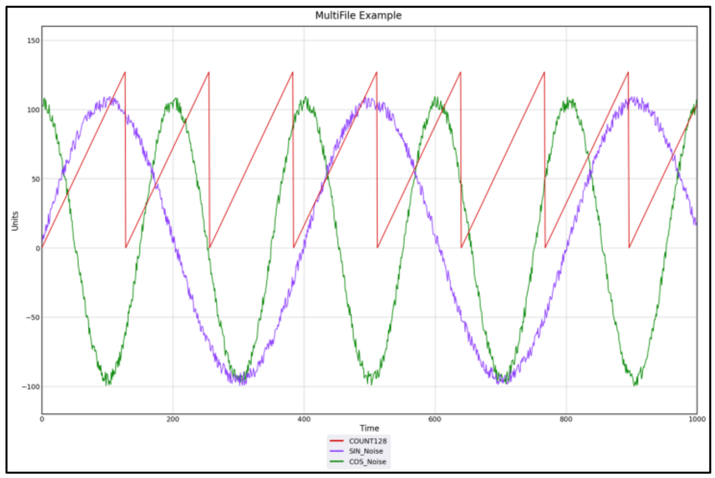

Figure 7. The MultiFile-Generated Version of Figure 2

SUMMARY AND CONCLUSIONS

The technical challenges faced in engine systems hot fire data assessment can lead to costly budget and schedule losses as well as unacceptable risk ignorance. Since 1994, NASA Marshall Space Flight Center's Engine Systems branch and its predecessors have continually developed a suite of analysis software tailored to industry needs. Underpinned by fast and efficient data processing, WinPlot and its companion programs enable rapid and efficacious data assessment throughout an engine's lifecycle. Whether supporting a hot fire real-time, investigating post-hot fire data, or communicating findings and risks to key decision makers, the capabilities effected by this mostly publicly available software are indispensable.

ACKNOWLEDGMENTS

The continual evolution of engine systems data analysis capabilities and technology is supported through NASA MSFC ER12, Engine Systems.

WinPlot was created by Roger Moody and is currently maintained by Derek Moody.

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