Software to Optimize the Testing of Mixed-Signal Devices

Gerard Stenbakken, Andrew Koffman, and T. Michael Souders
Electricity Division, U. S. National Institute of Standards and Technology[1],
Gaithersburg, MD 20899, USA
Phone (301) 975-2440, Fax (301) 926-3972, email stenbakken@eeel.nist.gov

Abstract

New software is now available to help test and measurement engineers optimize the testing of complex electronic devices. Examples of products that are benefiting from this software range from A/D and D/A converters to multi-range precision instruments. The software uses the empirical linear prediction methods developed at the National Institute of Standards and Technology (NIST) to reduce the cost of calibrating precision instruments. These methods have been written in a widely available commercial mathematical language. An easy-to-use graphical interface has been added to the software that makes use of the methods much simpler. The software allows the development of a model, the selection of an optimal reduced set of test points, and the prediction of the behavior at a larger number of points, along with confidence intervals for the estimates. These approaches are primarily aimed at analog and mixed-signal devices. An example of the use of this software is presented.

Introduction

The High-dimensional Empirical Linear Prediction (HELP) Toolbox is an optimization tool designed specifically to meet the requirements of test and measurement engineers. For many electronic devices and instruments, it is not physically or economically feasible to perform exhaustive testing. Therefore, test engineers must formulate abbreviated test plans that are economical to execute but still yield accurate measures of the overall performance of the tested products. The HELP Toolbox incorporates a new approach for optimizing the testing of electronic devices and instruments [1-5]. The method is currently being used by mixed-signal integrated circuit manufacturers to reduce the costs of testing their products, and it is also being used at the National Institute of Standards and Technology (NIST) to reduce customer's costs for selected calibration services [6]. Examples of products that can benefit from this approach range from multi-range precision instruments to programmable filters to integrated circuit A/D and D/A converters. Devices that are completely digital (digital inputs as well as outputs) are not supported.

The approach is based on a simple mathematical model that relates the device response at all candidate test conditions to a set of underlying variables. Once an accurate model has been developed, algebraic operations on the model are used to:

➡ select an optimal set of test points that will minimize the test effort required to achieve a specified level of confidence

➡ estimate the parameters of the model from measurements made at the selected test points

➡ predict the response of the device at all candidate test points (from measurements made at the selected test points) as a basis for accepting or rejecting units

➡ compute confidence intervals (uncertainty bounds) for the predicted response, and test the validity of the model, on-line

The entire process, including model development, can be performed with the HELP Toolbox, a NIST-developed graphical software package specifically tailored to this application. While a general understanding of the underlying principles is desirable, no mathematical programming is required of the operator. HELP places special emphasis on empirical modeling using measurement data collected previously on devices similar to the units under test. Empirical models require no detailed knowledge of the internal device architecture, yet they can be both accurate and efficient.

In addition to test optimization, the Toolbox is also useful for exploring the structures that underlie the behavior of tested devices. For example, it can reveal how many variables are actually needed to explain the behavior, and what their characteristic signatures look like. It can warn production engineers when the manufacturing process undergoes hidden changes, and it can even be used to help diagnose the likely causes.

While the Toolbox is intended for production testing applications, it is not designed for on-line use. Models are developed and tested within the Toolbox off-line, usually from empirical data on representative test units, and an optimal set of test points is selected. Once created, the models and test point vectors can be exported to the test system's on-line processor, which then drives the testing and calculates the predicted global responses of test devices from on-line measurements at the selected test points. The required

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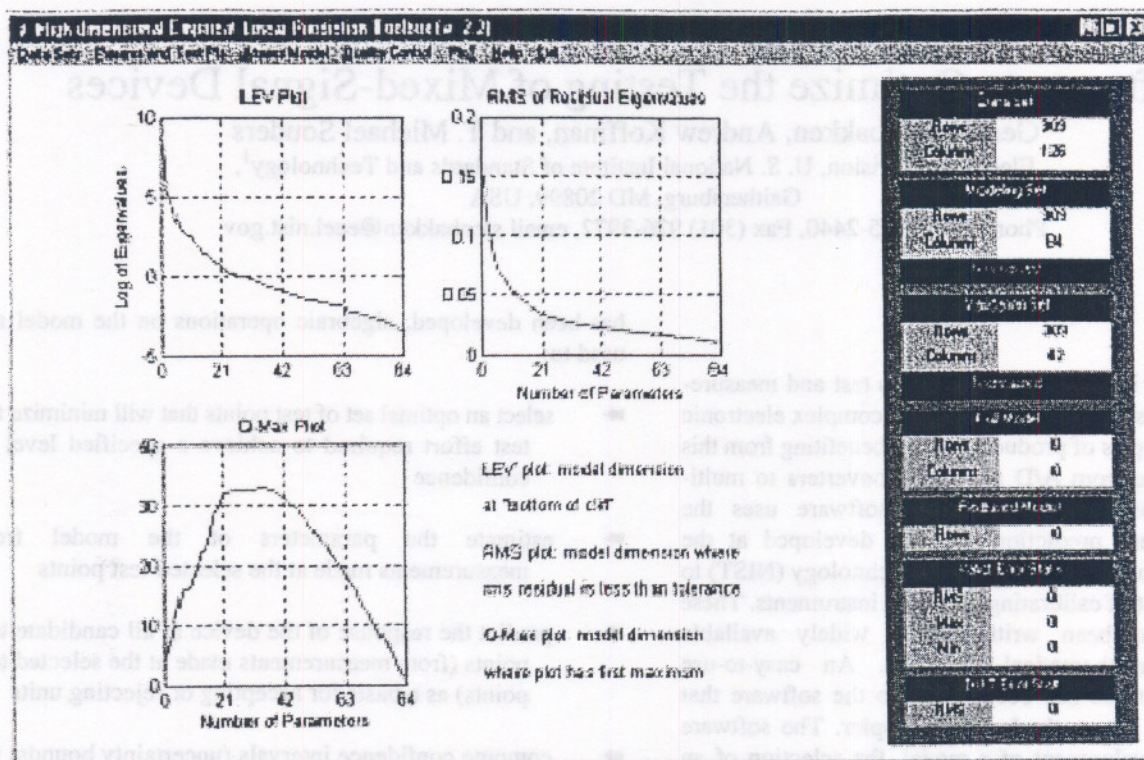1 Technology Administration, U. S. Department of Commerce

Figure 1. Toolbox control panel showing Console and Diagnostic Plots for Determining Model Dimensions.

calculations can be executed very quickly with any up-to-date personal computer or workstation.

The Toolbox software has been developed using the Matlab[2] programming environment and consequently requires that Matlab be installed on the host processor. While detailed knowledge of Matlab is not required, the user will benefit from some familiarity with it.

An Empirical Model of an Analog Instrument

As an example of the usage of the HELP Toolbox, consider the testing of an ac voltage measurement instrument. The HELP Toolbox has been used to reduce the costs of testing such instruments at NIST, by reducing the amount of testing that needs to be performed to achieve full coverage. The instrument is a relatively complex electronic device with input signal amplitudes ranging from millivolts to kilovolts, input signal frequencies from 10 Hz to 1 MHz, and many voltage ranges. A complete test of the instrument's performance requires a determination of its measurement errors at each of 309 specified test points which are combinations of range, signal amplitude, and signal frequency.

The cost of calibrating this instrument is expensive, with the cost of individual test points being several hundred

2 The mention of a commercial product in this paper is neither to be considered an endorsement by the National Institute of Standards and Technology nor to imply that it is the best available. It is mentioned only in the interest of completeness and to assist the reader.

dollars. As a result, considerable savings were realized by reducing the number of test points [6], while still being able to predict the accuracy of the instrument at all points of interest to the accuracy required by the manufacturer.

To develop an error model, measurement test data is first gathered on a number of typical instruments at all 309 candidate test points. The number of instruments to include is dependent on the number of parameters expected for the model. The set should include data from instruments that represent as wide a variety of manufacturing parameters as possible. In this example data was taken at 309 test points on 126 instruments manufactured over a long period of time. This array of data is read into HELP and separated into two groups. Data from two thirds of the instruments, 84, are used to build the model and the data from the other 42 instruments are used to validate the model. Selecting every third instrument for the validation set assures that the two data sets are not biased by any changes in the manufacturing process over time.

The manufacture's required test uncertainty varied from 5 ppm on some test points to over 500 ppm on others. To have the model give the proper weight to each test point, the data were normalized. In this case each test point is normalized by the manufacture's specified uncertainty level for that test point. Thus, plots given in this example are in these normalized units.

The measurement data has 309 degrees-of-freedom; however, the manufacturing process constrains the possible degrees-of-freedom for the instrument. The modeling process is a determination of the subspace within the 309-dimension space
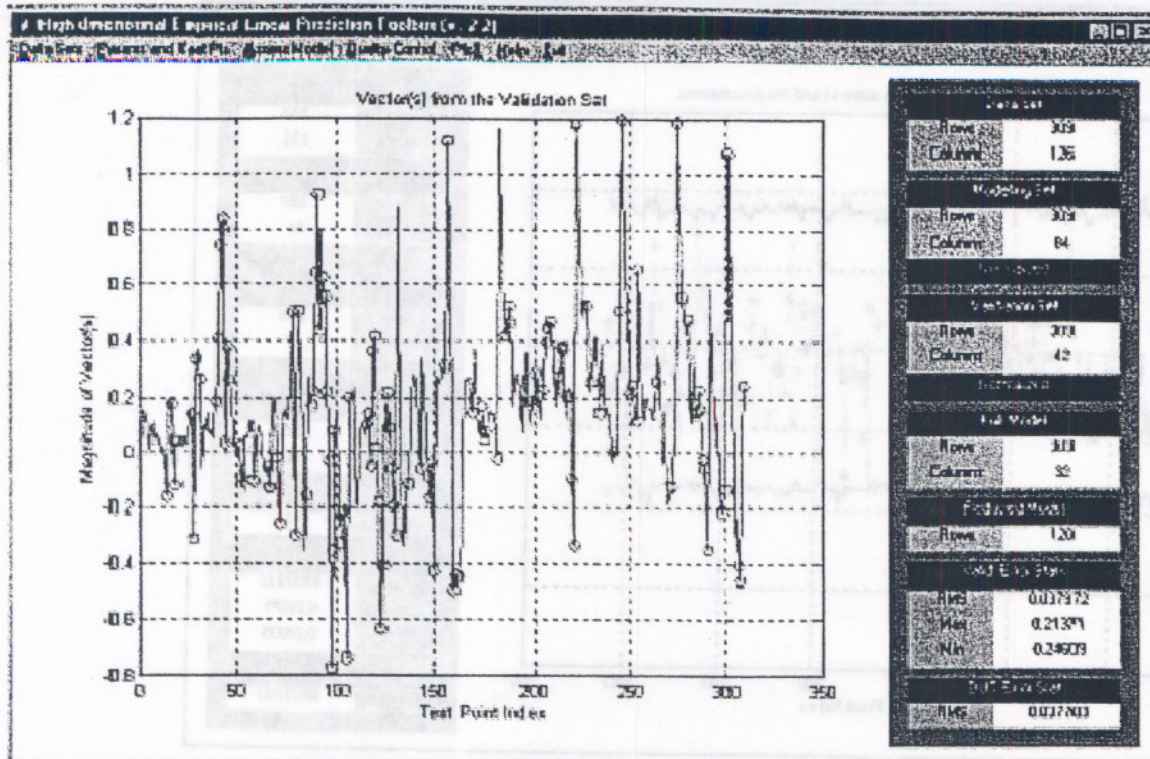
Figure 2. Toolbox control panel showing Measured errors at selected test points (circles) and at all 309 test points (line) for one of the instruments in the Validation Set.

that represents the possible instrument error behavior. If the measurement data contain all possible error behaviors, then the subspace represents the instrument error model. HELP uses routines that find the most efficient linear model to describe the possible error behavior.

Figure 1 shows the control panel for the HELP Toolbox version 2.2. Seven menu lists are available from the names shown on the bar near the top of the figure. Along the right is a console that shows the progress of the modeling. The console shows that the original Data Set of 309 test points (Rows) from 126 instruments (Columns) was divided into a Modeling Set of 84 instruments and a Validation Set of 42 instruments as described above. In the center of the figure are shown three diagnostic plots useful for selecting the size of the model. These are available after the Modeling Set has been analyzed by a singular-value-decomposition routine. The plots indicate the tradeoff of accuracy versus test cost, since more model parameters require more test points for their estimation. In this example they indicate that good models can be obtained with anywhere from 20 to 40 parameters

For this example, 32 model parameters were chosen. The process of choosing the best model size involves many factors. This will be described more fully below after other Toolbox features have been described. Once a model has been selected, it can be used to select the reduced set of test points. The test points are selected in a way that minimizes the prediction error at the points not selected. For this

example, 120 test points are selected. Thus, the model allows measurements to be taken at a combination of 120 ranges, frequencies, and amplitudes, and used to predict the instrument measurement errors at all 309 combinations of ranges, frequencies, and amplitudes.

The console in Fig. 2 shows that the Full Model is currently 309 test points by 32 parameters, and the Reduced Model has 120 test points (by 32 parameters, the same as the Full Model). Over the 42 instruments in the Validation Set, the rms value of the difference between the measured and the predicted values is only 0.038 normalized units, and the maximum and minimum differences are also given.

The plot in Fig. 2 shows the complete set of measured error values for one of the instruments used in the Validation Set. The circles are the 120 reduced measurement error values. The console shows that the rms value of the difference between the predicted values and the measured errors for the 120 reduced measurements for the 42 instruments in the Validation Set is 0.038 normalized units.

Since a complete set of measurements is available for the instrument used in Fig. 2, in addition to looking at the difference between the measured and predicted error values at the 120 reduced set of test points, we can look at the difference at all 309 test points. Figure 3 shows the difference between the measured and predicted error values at the 120 reduced test points as circles with a cross, and the 309 differences with the gray line. Also shown on this plot are the 95 percent
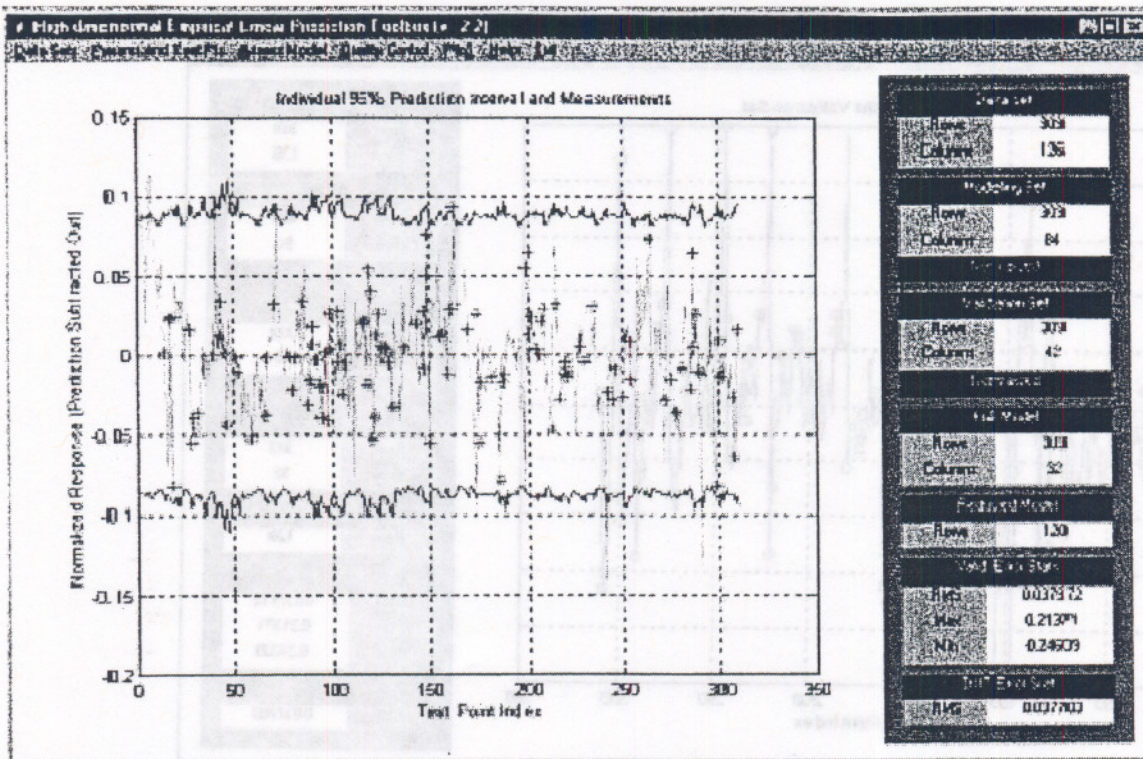
Figure 3. Toolbox control panel showing difference between measured and predicted errors for the 120 selected test points (circle with a cross) and all 309 test points (gray line). Also shown are the 95 percent confidence intervals for the errors at all 309 test points predicted from measurements at the 120 selected test points.
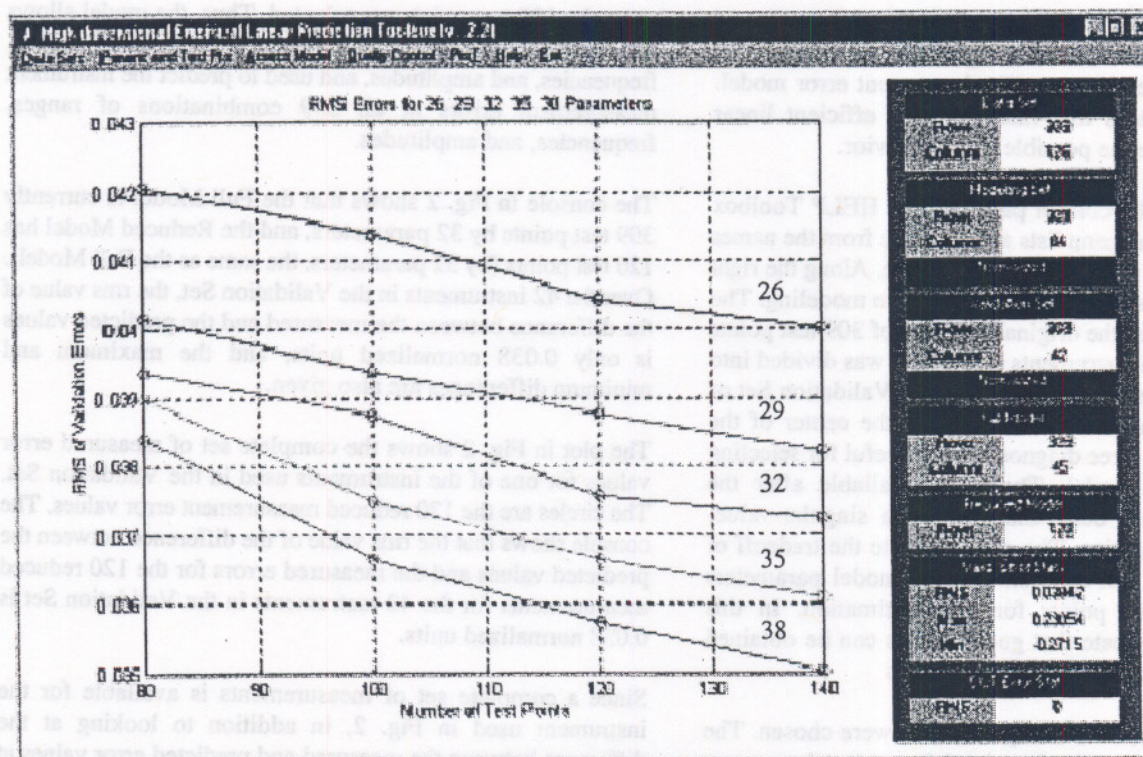

Figure 4. Toolbox control panel showing normalized rms errors for the Validation Set instruments as a function of five model sizes (26 parameters top line to 38 bottom line) and four different numbers of selected test points.

confidence intervals for predicting error values for 309 points from 120 measured values. In this example, 10 points out of 309 exceed these intervals. For 95 percent confidence intervals we would expect about 15 points to

exceed the interval. This accuracy is typical for the confidence intervals HELP predicts. Note that because of the way the 120 test points were selected the prediction intervals are very consistent across all the points. The vertical scale for this figure is very different from that in Fig. 2. The normalized differences shown are much less than one, indicating they are small with respect to the manufacturer's specified uncertainty.

So far, this example has described the development of one model and one set of selected test points. In practice one wants to optimize the choice of model size and number of test points. To assist this optimization process, the HELP Toolbox includes a feature that allows the examination of a number of combinations of model parameters and test points. Figure 4 shows the Validation Set rms differences for five different model sizes and four different numbers of test points. In this example the models always improve as the number of parameters increases. This seems perfectly normal but is not always the case [4]. In this example, the final choice for the model size and number of test points used also required the examination of the prediction uncertainty at all test points to assure that the manufacturer's test accuracy needs were met.

Conclusion

The new HELP Toolbox allows users to quickly and easily develop empirical models for their devices and instruments and to use the models to develop efficient methods for testing these units. The advantage of the toolbox is the ease of learning how to use these techniques and the speed with which such analyses can be carried out. NIST has published a User's Guide [7] on the theory behind the Toolbox and an introduction to the use of the software. NIST has also conducted a number of workshops on these techniques, with the last two incorporating the Toolbox software. The learning curve for students has been significantly improved with the use of this software.

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