UNDERSTANDING CORRELATION

Correlation analysis is a statistical method used to describe the degree to which one variable is linearly related to another. Correlation analysis is often used along with regression analysis to measure how well the least squares line fits the data. Correlation analysis can also be used by itself to measure the degree of association between two variables.

When performing correlation studies on probe card analyzers it is necessary to use the same probe card to correlate all of the systems in the study and, at the same time, isolate the variables presented by the probe card itself (array size, probe position, etc.) from the correlation results. In order to be of value, correlation studies performed on probe card analyzers must provide probe card independent results. The following section describes the standard method of correlation and discusses why it does not provide probe card independent correlation results.

STANDARD METHOD - COEFFICIENT OF CORRELATION

The standard method of describing correlation between variables uses the coefficient of correlation. The coefficient of correlation measures the strength of the linear relationship between two variables, x and y, and is computed (for a sample of n measurements on x and y) as follows:

$$ R = \frac{1}{n-1} \sum_{i=1}^{n} \frac{x_i - \mu_x}{\sigma_x} \frac{y_i - \mu_y}{\sigma_y} $$

where $\mu_x$ and $\sigma_x$ denote the sample mean and the sample standard deviation respectively for the variable x, and $\mu_y$ and $\sigma_y$ denote the sample mean and the sample standard deviation respectively for the variable y.

When using the coefficient of correlation, keep the following points in mind:

- R must be greater than or equal to -1 and less than or equal to 1 ($-1 \leq R \leq 1$)
- R and b (the slope of the least squares line) have the same sign
- R values near or equal to 0 implies little or no linear relationship between x and y
- R values closer to 1 or to –1 imply a stronger linear relationship between x and y
- R measures the correlation between x values and y values in the sample. Assuming a good sample, a similar linear coefficient of correlation will exist for the population from which the data points were selected.

Where the correlation coefficient approach to machine correlation does not provide meaningful information is when the range of data being measured is small compared with the standard error in the measurement. Such a situation may occur when measuring the alignment errors of an almost perfect probe card, as shown in Example 1. In this example, two probe card analyzers with near perfect correlation measure errors comparable in size to the measurement repeatability, and the correlation coefficient erroneously suggests poor correlation.
EXAMPLE 1

Standard Correlation Using Probe Position Data
Assume you are correlating analyzers using the X Error probe position values. If you were using a probe card with close to perfect alignment, the alignment results data would all be centered around the middle of the plot, as shown in Figure 1, Plot A.

However, if you were using a probe card with poor alignment, the results data would fall along a line similar to the one shown in Figure 1, Plot B.

In standard correlation studies, the slope of the line shown in Plot B of the previous figure would suggest good correlation. In this example, however, it simply demonstrates poorly aligned probes. More importantly, the results for both cards indicate a characteristic of the probe card rather than the probe card analyzer. In fact, the size of the probe card alignment error impacts the regression results to such a degree that the poorly aligned probe needles incorrectly imply better correlation!

RUDOLPH TECHNOLOGIES METHOD - DISTRIBUTION OF THE DIFFERENTIALS
The basis for a more reliable approach to quantifying machine correlation is to consider the statistical distribution of differences between a series of measurements made on two machines, and to compare this distribution with given accuracy standards. This approach produces a measure of machine-to-machine correlation that is completely independent of the probe card, and whose relevance is closely tied to the quantity of interest: accuracy specifications.

EXAMPLE 2

Correlation Using Distribution of the Differentials
Assume you are attempting to correlate two probe card analyzers: Machine 1 (M1) and Machine 2 (M2). A common fixture (F) is used with both machines. The accuracy of machines M1 and M2, and of the fixture F, can each be quantified to a desired level of confidence and verified to be within specified accuracy bounds. Also assume that the specified accuracies for M1 and M2 are aM1 and aM2, respectively, and that the specified accuracy for F is aF. As these accuracies are uncorrelated, the expected accuracy for the difference of measurements between the machines is then simply:

$$a_{\Delta M} = \sqrt{a_{M1}^2 + a_{M2}^2 + 2a_F^2}$$

If, for example, the accuracies of the two machines was aM1 = aM2 = 6.4 microns, and the accuracy of the fixture was aF = 3.8 microns, the expected accuracy for the measurement of machine differential would be a_{\Delta M} = 10.5 microns (refer to Figure 2).

Figure 2 graphically shows the probability density functions of each of the error sources, as well as the expected probability density of the differential error. This expected differential accuracy, a_{\Delta M}, is then the standard against which the measured distribution of machine differentials are judged. A small measured distribution of machine differentials compared with the expected differential accuracy corresponds to good machine-to-machine correlation.

This correlation method is entirely probe card independent — array size and probe position do not contribute to the final correlation results.
CONTROLLING THE VARIABLES
Correlation between probe card analysis systems depends on many system, process, and environmental variables. A thorough understanding of these variables is critical for close correlation between systems. Moreover, there can be no relevant or conclusive discussion of correlation between systems until certain guidelines that assist in controlling these variables have been met.

Once the variables are controlled as described below, we assume that probe card performance will be very repeatable in position over a short period of time.

System Variables
System variables are by far the most significant factors in the correlation of probe card analysis systems. The guidelines described below discuss the requirements necessary to control these variables.

• Run a GR&R study on each system to be correlated.
• Use a clean, fairly new probe card with a medium number of probes (300-1000). Too many probes places too much of a load on the system, while too few probes can lead to sampling errors. Additionally, all of the probes in the array must fit on the checkplate in a single touchdown (Max Array Size = 2.5”(X) x 2.2”(Y)).
• Use the same Rudolph Technologies motherboard on all systems. If the same motherboard is not used, test results will contain deflection data that reflects the differences between the motherboards.

IMPORTANT Spring Rate has a direct impact on the measured alignment and planarity position of probes. The spring rate of non-Rudolph motherboards is not known; correlation results cannot be predicted.

• Calibrate each system to ensure performance to factory specifications. In particular, the stage and imaging systems must be accurately calibrated.
  • Stage Performance: Ensure that all fiducials are in focus by completing a Vision Gage Card Mapping. Look for “smooth” map results. A “noisy” Vision Gage Card mapping result will compromise correlation. The software does contain a “flyer” algorithm that removes large errors, but a very noisy map, with spikes of +/- 0.5 mils, is not a good indicator of successful system correlation.
  • Imaging System Performance: Ensure that the pixel size of the camera, the XY window positions, and the illumination are calibrated to factory specifications. If illumination is not calibrated, there may be issues with illumination uniformity. All of these can have a negative impact on image processing and repeatability.
    • NOTE Prior to running the Illumination calibration, ensure that the background offset values in the CP.INI files are set either to their default values or the same value for all systems in the correlation study.
    • Z Calibration: Uncalibrated machines are the primary cause of planarity jumps during retest. The Z Calibration can be a potential source of probe depth errors between correlating systems/sites. If one of the parameters you wish to correlate is probe depth, we recommend setting the Z-Cal dimension to 20 mils on all of the systems in the correlation study to reduce the chance of operator-induced errors.
• Control fixture-dependent measurement errors, particularly probe card drift. Run the Fine Leveling procedure to check for accuracy and repeatability issues that may impact XYZ alignment and planarity test results. Check for Actual Probe Depth drift between tests. Actual Probe Depth is found in the Extended Header. If this parameter is changing between tests, the probe card is moving in the motherboard during the test. There are three control variables used to control probe card drift, all located in the C:\Windows\CP.INI file.
  • SettleTDS=5. This variable controls the number of exercising touchdowns the system performs prior to commencing the actual planarity test. The exercising touchdowns press against the needles a defined number of times to help settle the probe card in the motherboard. The default setting is 5. If drift is evident, change the SettleTDS variable to 15 or 25. This increases the test time by a small margin but has a significant impact on probe card drift.
  • ForceHinge=1. This variable toggles the dialog box forcing the operator to hinge the support plate to the hinged position and clean the checkplate. The purpose of this message is to relieve residual stress between the two halves of the motherboard (top and bottom). The stress is caused by uneven pogo pressure as a result of hinging the motherboard and the pogos contacting one side of the probe card first before closing. Change the 1 to a 0 to turn the message off.
RetestPlanar=1. This variable toggles the system to perform a final retest of all the non-bussed probes at the end of the test. The average planarity of the retested non-bussed probes will be averaged into the planarity results of all previously tested probes. This helps minimize probe card drift on test results.

- Use the same checkplate on all systems.
- Ensure that system precision is the same on all systems. Set the Precision value to 3 for mils or 1 for microns in the [Info] section of the C:\Windows\CP.INI file.
- Ensure that all other CP.INI settings are identical between systems.
- Ensure that the same reference file and the same version of the PrecisionWoRx software is being used on all systems.
- Clean the probe card before each test. CRes test results should be less than 2 ohms.
- Ensure the test measurement resolution is the same on all systems. Set the Z Resolution to .25 microns (0.01 mils) in the Utilities/Configuration dialog box.

**Process Variables**
Ideally, the probe card and motherboard should be mounted using exactly the same method on each system to be correlated. The best way to achieve this is to have the same operator mount the probe card and motherboard on each system. When this is not possible, deviations can be kept to a minimum by using the same torque pattern when mounting the motherboard and probe card. The correct torque pattern can be found in the documentation included with your motherboard. If there is no documentation, contact Rudolph Technologies for a new set. For large array probe cards, variations in probe card mounting techniques can be the largest contributor to correlation failure.

**Environmental Variables**
The following environmental variables must also be controlled during correlation studies.

- Temperature and Humidity. Verify that the environment of the machine is within specification.
  - Temperature: 68° ± 3°F (20° ± 1.6°C) 
  - Humidity: 30% to 39%. Note that the humidity range for correlation is tighter than the standard system humidity specification, as humidity over 40% may cause leakage deviations.
- Lighting. If the system is located next to a window, changes in ambient light levels from day to night may cause system performance loss. This is very important, particularly when testing cards with large arrays over a long period of time. Probe cards most susceptible to ambient light changes are those with very small probe tip diameters and radius-tip probe cards.

**CORRELATION PROCESS**
Once all of the variables in the previous section have been addressed, use the following procedure to correlate your systems.

1. Test the probe card for the parameter(s) of interest on each system to be correlated, n number of times (n must be ≥ 10).

2. Compute the differentials for the parameter(s) you want to correlate (X Error, Y Error, etc.). Example: Assume that two systems (System 1 and System 2) are being correlated for X Error and n = 10.
   - For System 1, calculate the average X Error value for each probe by adding all of the test results for that probe together and dividing the result by n.
     \[
     X_{ErrAVG} \text{ for Probe } 1, \text{ System 1} = \frac{X_{Err1} + X_{Err2} + X_{Err3} + X_{Err4} + X_{Err5} + X_{Err6} + X_{Err7} + X_{Err8} + X_{Err9} + X_{Err10}}{10}
     \]
   - Repeat Step A to calculate X_{ErrAVG} for all of the probes on System 2.
   - Calculate the differential between the X Error averages on the two systems for each probe.
     \[
     \text{XErrAVG for Probe } 1, \text{ System 1} - \text{XErrAVG for Probe } 1, \text{ System 2} = \text{Probe 1 Differential}
     \]
   - Calculate the 3 sigma value of the group of differentials for the parameter(s) of interest.
   - Compare the actual differences to the expected differences to ensure appropriate accuracy values for the parameter(s) of interest, as described in Example 2.

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