Computer-aided 3D tolerance analysis of disk drives

by B. Schlatter

Disk drives are multicomponent products in which product build variations directly affect quality. Dimensional management, an engineering methodology combined with software tools, was implemented in disk drive development engineering at IBM in San Jose to predict and optimize critical parameters in disk drives. It applies statistical simulation techniques to predict the amount of variation that can occur in the disk drive due to the specified design tolerances, fixturing tolerances, and assembly variations. This paper presents statistics describing the measurement values produced during simulations, a histogram showing the measurement values graphically, and an analysis of the process capability, C_{pk}, to ensure robust designs. Additionally, it describes how modeling can determine the location(s) of the predicted variation, the contributing factors, and their percent of contribution. Although a complete 2.5-in. disk drive was modeled and all critical variations such as suspension-to-disk gaps, disk-stack envelope, and merge clearances were analyzed, this paper presents for illustration only one critical disk real estate parameter. The example shows the capability of this methodology. VSA®-3D software by Variation Systems Analysis was used.

Introduction

Today, shorter development cycles and customer demand for higher reliability dictate predictive tolerance modeling during the conception and development phases of the disk drive product cycle. Also, the continued trend to smaller disk enclosures (DEs) with tighter disk spacing in particular and smaller space margins in general calls for precise 3D (spatial) analysis; traditional 2D (planar) analysis with simplifying assumptions is inadequate in today's competitive environment. More often, design margins are too small for worst-case analysis, and some type of statistical analysis must be used.

Historically, dimensional management in DASD was often reactive: too late and too fragmented. Typically, a tolerance study was done when problems showed up during product ramp-up. At that time, however, parts and processes were more or less set, and engineering changes were expensive and disruptive. Also, a tolerance study done at that time in the life of a product typically had to be started from scratch, and was limited and focused on one area of the disk drive. Tolerance studies consisted of "back-of-the-envelope" calculations, or at best simple spreadsheet studies which were limited to planar analysis.

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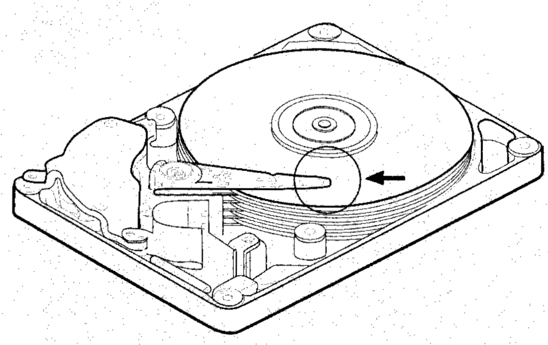

Figure 1

2.5-in. disk drive without top cover.

Three-dimensional effects were usually ignored or assumed to be worst-case, which is wasteful for multicomponent assemblies.

In 1991, 3D tolerance analysis was first used at IBM San Jose on a 5 1/4-in. form factor (FF) disk enclosure (DE). Although this type of tolerance analysis had been applied in the automotive industry for years, this was the first application on a disk drive product. This DE contained a linear-type actuator, which made the modeling effort somewhat complex in contrast to that required for today's typical rotary actuator.

In early 1992 a 3D tolerance model was developed for a 2.5-in. FF disk drive with a rotary-type actuator (see **Figure 1**). The VSA®-3D tolerance tool was used successfully on the spindle/motor in predicting runout, disk-stack envelopes, and imbalance numbers. Several "what-if" studies were also done for various designs and for different tolerance assumptions. For the merge operation (inserting head and arm assemblies between disks), the merge fixture was generated and integrated into the overall model, enabling the designers to analyze and optimize merge gaps. The suspension-to-disk gaps were also studied, and different designs were compared (stacked arm actuator vs. insertable arm actuator, etc.).

The area most beneficial for modeling was that of disk real estate parameters, because there were a large number (about 80) of detail and fixture tolerances and assembly variations which contributed to real estate margins—too complex to handle using traditional tolerance analysis. The term *disk real estate* (disk mapping) refers to the relationships among the head element/slider and the disks. One of the disk real estate parameters is presented in this paper to demonstrate the capability of the 3D tolerance method.

General discussion

The 3D model development and analysis process [1] includes the following twelve steps:

1. Understanding of objective and scope.
2. Gathering of design and process information.
3. Flowcharting of assembly steps.
4. Definition of detail geometry.
5. Specification of dimensional variation.
6. Specification of assembly methods.
7. Specification of measurements.
8. Writing and compiling of the model file.
9. Model debugging.
10. Running simulations.
11. Analyzing results.
12. Performing "what-if" studies.

• *Understanding of objective and scope*

First one must understand the capabilities and limitations of this methodology. It is not a solid modeler. Only after an assembly has been analyzed for nominal parts, tools, or assemblies are variations applied to see whether the product functionality meets the design requirements. VSA-3D software is a Monte Carlo simulation method that allows the designer to "virtually" build thousands of disk drives even before prototypes are made. Component, tool, and assembly variations are accounted for. After the virtual assemblies are built, VSA-3D can report to us, with statistical accuracy, geometric (gaps, clearances, runouts, etc.) or nongeometric (imbalance, gram-load, etc.) information about the design. VSA-3D is not a finite-element modeler; components are rigid body members.

• *Gathering of design and process information*

The modeler had to work closely with the design community to gather the latest information on components (print geometry and tolerances), assembly methods (self-aligning or fixtures), assembly variations, assembly sequence, and geometric design specifications. This was no small task, since extensive changes occurred during the concept stage. Also, because the three groups (Heads, Disks, DE) designing this drive were at different physical locations, keeping up with the latest designs was not easy. Since 3D tolerance was a new approach, negative reactions by some designers had to be overcome. Most became advocates once they saw the power of this tool to take the mystery out of tolerance assignment.

• *Flowcharting of assembly steps*

VSA-3D has a preprocessing program, the Variation Simulation Analysis Builder (VSAB), which is an interactive graphics interface for creating the model. VSAB interfaces with CAD programs. However, since solids were not initially available, the VSAB was used only to create the assembly flow diagrams (AFDs). The AFD of a typical head suspension assembly (HSA), which is a subassembly of the DE, is shown in **Figure 2**. Note that details are depicted as rectangles, fixtures as ovals, and subassemblies as squares. The AFD of the whole DE model consists of 70 details, 25 fixtures, and 25 subassemblies.

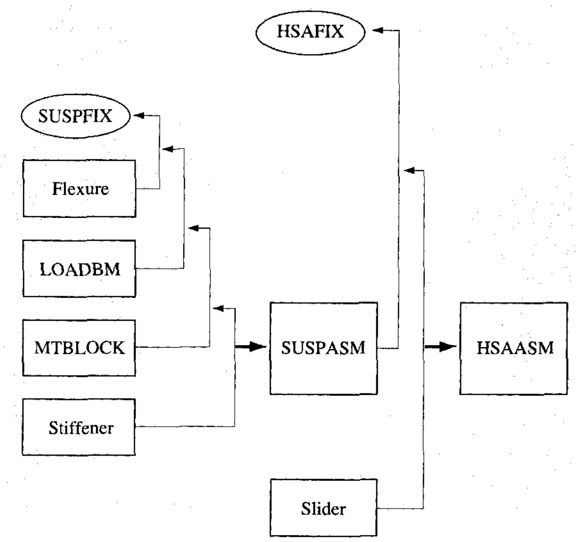

Figure 2

Flow diagram of head suspension assembly.

- *Definition of detail geometry*

Detail parts drawings are required for this step. After judicious selection of the appropriate modeling points, the Variation Simulation Language (VSL) files were created. This was done using the E! editor [2], which is a full-screen editor well suited for VSL. The VSL computer language was developed specifically for writing the assembly variation models used by VSA-3D. International Geometry Exchange Standard (IGES) files of the solids were not available in early 1992 because half of the parts were generated in 2D CADAM. IGES files with VSAB could have saved time creating the detail definition files. (Seamless integration of the VSA-3D software with popular CAD systems will soon be available and will simplify this step.)

- *Specification of dimensional variation*

The source for the tolerances was the drawings and the product specifications. Familiarity with geometric dimensioning and tolerancing (GD&T) standards (ANSI Y14.5) was essential, because that tolerancing scheme was used on the blueprints of this 2.5-in. FF disk drive.

This tolerance information was added to the appropriate definition file using the VSL syntax. It was necessary to define variation and direction, and to add statements to deviate point locations. This version of VSA was point-based; a feature-based version (planes, holes, etc.) is now available. There are eight probability distributions to choose from when defining variations. The normal distribution is most often used, except for true position angular variation, for which the uniform distribution is usually chosen. There were more than 700 tolerances in this 2.5-in. disk drive model.

- *Specification of assembly methods*

Virtual assembly of the parts was also done with VSL files. Mathematical statements are used to rotate and to translate components and subassemblies from an initial location in space to an assembled location. The way components are positioned during assembly determines which of the moves NET, 321, Planar, or General is chosen.

- *Specification of measurements*

Measurements too were created in files with the VSL syntax. A measurement can be a distance, an angle, or a value. The 2.5-in. DE model had about 100 individual measurements (outputs).

- *Writing and compiling of the model file*

The VSL model file is the "skeleton" that holds together and sequences all of the definition, fixture, assembly, and measurement files. This is the actual model VSA-3D used to run the build simulations.

- *Model debugging*

Before a model can be used, it must be compiled. During compiling, the syntax is checked. Errors are flagged and must be corrected. Syntax errors are usually easy to fix; problems with assembly files are more complex, because no graphic display of the "post" assembly exists. Future VSA-3D releases are expected to have this capability.

- *Running simulations (Monte Carlo method)*

One simulation consists of a single execution of the model. First, all of the variation sources are initialized to a value chosen at random from the statistical distribution. Then all of the model statements are processed using these values. A single value is produced and stored for each of the measurements; multiple simulations produce multiple measurement values. Typically 3000 simulations are sufficient for a well-defined output distribution. To perform 3000 simulations of this model takes about

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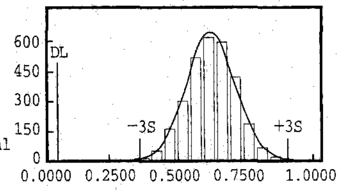
ODT_DEP1/ SVO Elem (ODCST) to OD Data end 30.25 3000 samples

Nominal: 0.6096
Mean: 0.6095
Standard Deviation: 0.0921
Lower Design Limit: 0.0000
Upper Design Limit: N/A
Cp: N/A
Cpk: 2.3788
Distribution: Tested Normal



	Actual	Est		Actual	Est*
% < Low Limit	0.0000	0.0000	Low	0.2861	0.3332
% > High Limit	N/A	N/A	High	0.9245	0.8858
% Out of Spec	0.0000	0.0000	Range	0.6384	0.5526

95% C.I. for % Out of Spec: 0.0000 to 0.0000 *Est Range: 99.7300

Figure 3

Typical process report for ODT_DEP1 measurement.

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ODT_DEP1 Head Element to outermost Data track (30.25) @ OD CS Touch

Nominal at Median: 0.6125
HLM Variance: 0.0081 High-Low-Median Study

Tolerance			Effect
AD1_X04b	Head/Susp. slider location	+/− 0.15	28.37%
ED000000	Servo Write radial error	+/− 0.12	19.83%
AX000014	Hub Arm stop distance to bore center	+/− 0.015	15.43%
CSPOS2	Base cartridge mount hole position	TP 0.05	4.02%
AI000005	Tab to slot misalignment	+/− 0.05	3.15%
AX000011	Snap Hub slot parallelism to -B-	// 0.10	3.15%
AI000004	Air gap		2.77%
AG000005	Cartridge shaft base axial runout to -B-		2.12%
AX000013	Hub crash stop extension angularity		1.94%
CSPAR2	Base cartridge mount parallelism		1.91%
CSPOS3	OD crash stop mount hole position		1.82%
CG100003	Slider Rail Symmetry		1.63%
AB100001	OD Crash Stop radius		1.24%
AE1_X007	Head/Arm fixture Suspension slot pin symmetry		1.23%
AE100002	Head/Arm asm Suspension float @ slot		1.23%
AD1_X005	Head/Susp. slider location		1.16%
AI000007	Cartridge in contact with Snap Hub bore		1.02%

			92.03%
60 additional contributor(s) < 1.00% each			7.97%

Figure 4

HLM report for ODT_DEP1 measurement.

20 minutes on the IBM RS/6000™ 530H workstation. The output distributions or process can be analyzed to determine how much variation is occurring and where it comes from.

HLM (high-low-median) analysis is a full-factorial experiment built into the analysis program. It is used to determine the sources of tolerance variation that are causing variation in the assembly characteristics being measured. HLM analysis is done by running a specific set of simulations independent of Monte Carlo simulations. In a three-level HLM (five-level HLM is optional), the simulations vary each input to its high, low, and median values, one at a time, while holding all other inputs at their median values. Only main effects (effect of a variable all by itself on the output measurement results) are calculated. Interactions are done by grouping, in which the simultaneous variation of more than one variable is considered and the main effect of the entire group of variables on an output measurement is determined. Running the HLM for the disk drive model takes about two hours on the RISC System/6000.

- *Analyzing results*

Various presentations of the simulation results can be displayed on the computer screen and/or printed in various standard and custom reports.

- *Performing "what-if" studies*

Once a basic model is generated, it is easy and simple to change tolerances (type or magnitude) with a few keystrokes and to run simulations with different inputs. Important insight is quickly gained. If the geometry of details or tooling or process changes, however, modifications to the model are naturally more involved and time-consuming.

Disk real estate parameter output analysis

An in-depth look at two of the output measurements follows. First, the measurement ODT_DEP1 is an example of a normal distribution output, and the design margin is large ($C_{pk} = 2.3$). Second, the measurement IDPC_CR2 is an example of an abnormal output; the design margin is too small ($C_{pk} = 1.2$). The meaning of C_{pk} and the use of process reports and high-low-median reports are now presented and explained.

- *Measurement ODT_DEP1*

Measurement ODT_DEP1 is the distance from the center of the head element to the outermost data track (in the disk plane) when the actuator is touching the OD crash stop. This gap is critical, because if it goes to zero the drive servo function fails permanently.

Process report

Note that the output report shown in **Figure 3** contains statistics describing the measurement values produced during simulations, process capability (C_{pk}), and a histogram showing the measurement values graphically.

The distribution tested was normal and C_{pk} was calculated as follows:

$$C_{pk} = \frac{mean - LDL}{3\sigma},$$

where *mean* and σ are the mean and standard deviations of the sample data, and *LDL* is the lower design limit. Note that $C_{pk} = 2.4$ is an excellent process capability (for "built-to-print" parts, less than one DE per million should fail for this parameter).

HLM report

As shown in **Figure 4**, the head/slider location tolerance is by far the largest contributor to this variation (28%). Two more are over 10%, fifteen are over 1%, and 59 additional tolerances are less than 1% each. Knowing for a given output which tolerances are important and which are not is most useful and takes the guesswork out of tolerancing.

- *Measurement IDPC_CR2*

Measurement IDPC_CR2 is the distance from the inner suspension tab to the spacer ring (in the disk plane) when the actuator is compressing the ID crash stop. This gap is critical: If it goes to zero, the suspension is touching the spacer ring, which is a catastrophic condition.

Process report

The output distribution shown in **Figure 5** is obviously not normal; in fact, it is a Pearson-II distribution. For this case C_{pk} was calculated as follows:

$$C_{pk} = \frac{mean - LDL}{mean - X_1},$$

where *mean* is the mean of the sample data, *LDL* is the lower design limit, and X_1 is the value at the 0.00135 percentile. $C_{pk} = 1.2$ is not a large enough process margin. A failure rate of 0.033% is not acceptable for this parameter.

HLM Pareto chart

In the Pareto chart shown in **Figure 6**, the ID crash stop pulse compression is the overwhelming variation (82%). To improve C_{pk}, this variation source was controlled by making design changes to the crash stop.

Conclusions

Variation Simulation Analysis as a development methodology has been accepted and embraced by the product engineering community in San Jose, and other Storage Systems Division PE groups are evaluating this method. Several other manufacturers in the disk drive industry are using VSA-3D.

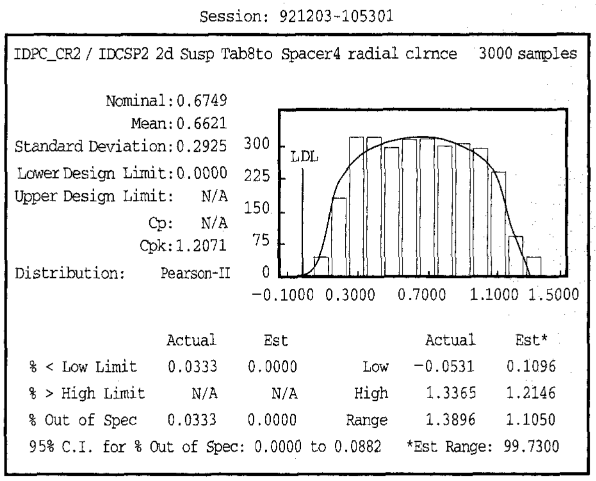

Figure 5

Abnormal process report for IDPC_CR2 measurement.

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IDPC_CR2 / IDCSP2 2d Susp Tab8to Spacer4 radial clrnce

Nominal at Median: 0.6848
HLM Variance: 0.0322

High-Low-Median Study

Tolerance	Effect
AB200003 ID Crash Stop pulse compression	81.86%
AX000012 Hub crash stop extension angularity	4.44%
AX000014 Hub Arm stop distance to bore center	3.94%
AG000005 cartridge shaft base axial runout to -B-	1.14%
CSPOS2 cartridge mount hole position	1.01%

	92.39%
56 additional contributor(s) < 1.0% each	7.61%

Figure 6

HLM Pareto chart for IDPC_CR2 measurement.

The VSA-3D tool provides valuable help and feedback to assist the designer/engineer in understanding the effects of tolerance variations. They can now make intelligent tolerance assignments, meet design goals, and eliminate potential mechanical problems. Tolerance modeling is not only useful during the development phase of the DE. Later, when production parts tolerance data become available, they can be added to the model in place of the assumed input distributions. Or "out-of-spec" parts tolerance data can be added and studied in order to make "off-spec" decisions.

A modeler must be trained and skilled in the areas of VSA method, VSL programming, mathematics, geometry, 3D visualization, ANSI Y14.5 GD&T, AIX®, statistics, and tooling. Faster computers, a seamless interface with 3D modelers and 3D assemblers, and artificial intelligence are on the horizon, and designers will be able to take a more active role in dimensional management.

Acknowledgments

R. Heggem, manager, VSA Western Division, brought VSA-3D to IBM San Jose and taught us much about variations and tolerancing. C. Polson was a valuable consultant as we learned the programming computer aspects of VSA-3D. Also, thanks are due to D. P. Fazzio and L. J. Gilliland for management support during our development of the VSA-3D methodology.

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Received July 11, 1995; accepted for publication May 30, 1996

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