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EXTENDING SYNTHESIS: ROBUST DESIGN USING ADAMS/INSIGHT

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ABSTRACT

Mechanical Dynamics Inc. has entered its twenty-sixth year of producing ADAMS® (Automatic Dynamic Analysis of Mechanical Systems), the world's leading commercial mechanical analysis software for kinematics and dynamics of multibody systems. During the past twenty-five years, use of mechanical analysis software has grown dramatically. No longer the province of a fringe group of highly trained specialists, it now has a presence on nearly every engineer's desktop. The software comes in many forms—embedded in Computer Aided Design (CAD) software, or as stand-alone packages such as ADAMS. Use of the software even has a new name: Functional Virtual Prototyping refers to the ability to use mechanical analysis software to complete the engineer's understanding of the physics of a design without the need for prototype parts.

Due to large numbers of mechanical systems, a high cost of prototypes, and relentless pressure on cost and safety, the automotive industry has always been at the vanguard of the use of Functional Virtual Prototyping technology. A recent popular trend in the automotive industry is called the Six Sigma process—intended to get as close as possible to zero defects—in part by assuring robust quality and performance of components, subsystems, and systems. To satisfy the demands of the Six Sigma trend, the automotive industry now uses Functional Virtual Prototyping software such as ADAMS as an important tool in Robust Design. This paper describes new software for Robust Design, called ADAMS/Insight, and illustrates how the behavior of a mechanical system model in ADAMS can now be understood more completely over a range of system parameters and tolerances.

Keywords: ADAMS, Design of Experiments, Robust Design, Six Sigma, kinematics, dynamics

BASIC DEFINITIONS

Functional Virtual Prototyping refers to the process of using software such as ADAMS to build computer models of mechanical systems with sufficient fidelity so that they represent the actual behavior of the mechanical system well enough so that the computer model can serve the same purposes as a physical prototype of the system. A physical prototype of a product or system is generally tested in multiple operating conditions; multiple prototypes are typically required to examine different design parameters. The prototypes are instrumented to record a variety of engineering performance data such as motion, loading, vibration, and durability. This same information is available from a single Functional Virtual Prototype.

The **Six Sigma** process, as discussed in this paper, has its origins in the statistical concept of standard deviation and the sigma symbol (σ) typically used to denote standard deviation. A strict mathematical interpretation of defect counts would result in a six sigma criteria of not more than 2 parts per billion defective. However, the Six Sigma process assumes a distribution which can shift off center as much as +/- 1.5σ, and therefore the defective part rate traditionally associated with Six Sigma is actually 3.4 parts per million. In addition to the mathematical measurement, the Six Sigma process also encompasses a corporate philosophy involving aspects of management, finances, customer interaction, and process predictability, which contribute toward the goal of zero defects.

Robust Design refers to a product design that behaves predictably and reliably, even as manufacturing tolerances, material properties, or operational parameters change. Within the context of this paper, Robust Design is combined with Functional Virtual Prototyping to determine the region of the design space where the performance of the system changes insignificantly when design factor settings are varied a small amount.

DESCRIPTION OF ADAMS AND ADAMS/INSIGHT

ADAMS is commercially available software for Functional Virtual Prototyping of mechanical systems, which allows the user to simulate and visualize 3D motion and force behavior under realistic operating conditions. With the ADAMS/Insight add-on module, users can quickly explore multiple design variations, test, and refine until system performance is optimized.

ADAMS automatically converts a graphically defined model to dynamic equations of motion and then solves the resulting set of combined differential and algebraic equations. ADAMS can resolve redundant constraints, handle unlimited degrees of freedom, and perform static equilibrium, kinematic, and dynamic analyses. It can also simulate systems with both rigid and flexible parts undergoing elastic deformations. In addition to displacement, velocity, acceleration, and force outputs, users may request a variety of other data, such as graphics output and data for subsequent finite element analysis or control systems analysis. Users can impose a variety of constraints such as joints, joint primitives, time-dependent motions, higher-pair contact, and user-written subroutines. Users may also implement forces that act in an action-reaction sense between a pair of points in the system, or apply forces to a single point from an external source.

An ADAMS model represents the physical attributes of the movable elements (parts) in a mechanical system. Geometry can be defined from either the ADAMS library of simple parts, or from imported CAD geometry. Constraints and motions are used to prescribe how parts are attached and how they are allowed to move relative to each other. Forces can be applied to a model to affect part motion and reaction forces on constraints. Available libraries of forces include flexible connectors, such as springs, dampers and bushings; special forces, such as aerodynamic forces and tires; applied forces based on general functions; and contact elements acting between solid bodies in the model.

A simulation can be initiated at any point in the modeling process to verify its performance. ADAMS automatically calculates predefined information for the objects in the model, such as forces, displacements, velocities, acceleration, and kinetic energy. Once basic performance characteristics of the model are known, the model can be refined with enhancements such as applying friction between bodies, defining control systems using linear or general state equations, and incorporating flexible bodies or flexible connectors. Using ADAMS data to establish quantitative performance characteristics, or metrics, is an important step toward understanding the behavior of the mechanical system. The performance characteristics chosen will then become “responses” when using Design of Experiments and Optimization, available in ADAMS/Insight, companion software to ADAMS.

To help to compare alternative designs, you can easily parameterize most entities in your ADAMS model, including geometric points, mass properties, force characteristics, etc. These parameters then become “factors” when studying your mechanical system model in detail using Design of Experiments and Optimization available in ADAMS/Insight.

ADAMS/Insight enables the design of sophisticated experiments for measuring the performance of a mechanical system model. It also provides a collection of statistical tools for analyzing the results of experiments to better understand how to refine and improve the model [1].

DESIGN OF EXPERIMENTS

Experimental design (also called Design of Experiments or DOE) is a collection of procedures and statistical tools for planning experiments and analyzing the results. In general, the experiments measure the performance of a physical prototype, the yield of a manufacturing process, or the quality of a finished product [1].

Although experimental design techniques were originally developed for physical experiments, they also work very well with virtual experiments. For simple design problems, the behavior of a mechanical system can be explored and optimized using a combination of intuition, trial-and-error, and brute force. As the number of design options increase, however, these methods become ineffective in formulating answers quickly and systematically. Varying a single factor at a time does not yield information about the interactions between factors, and trying many different factor combinations will require multiple simulations resulting in a great deal of output data to evaluate. To help expedite multi-response, multi-factor experiments, ADAMS/Insight provides planning and analysis tools for running a series of experiments. ADAMS/Insight also helps to determine relevant data to analyze, and automates the entire experimental design process [1].

A simple series of steps enables the study of an ADAMS model using ADAMS/Insight. These steps are covered in detail in [1] but can be summarized as:

- Import an ADAMS model with factors and responses to ADAMS/Insight
- Create an experiment design
- Use ADAMS/Insight to run the required ADAMS simulations
- Fit the resulting response data to a response surface
- Evaluate the quality of the fit
- Publish the data via HTML or spreadsheets

ROBUST DESIGN ILLUSTRATION

This section illustrates the process of Robust Design using the Design of Experiments capability within ADAMS/Insight. ADAMS/Insight is used to perform a virtual experiment using a Short Long Arm (SLA), independent front suspension model from ADAMS (see Fig. 1). The resulting data are fit with a polynomial to determine the factors that most affect the performance of the suspension. The results are published to an HTML page that can be viewed with a Web browser. The simulation chosen for this virtual experiment is analogous to the vertical wheel travel event on a kinematics and compliance test machine—the suspension is exercised through its range of vertical motion while the steering input is held constant in the straight-ahead position. Table 1 describes the complete topology of the simplified suspension used for this example.

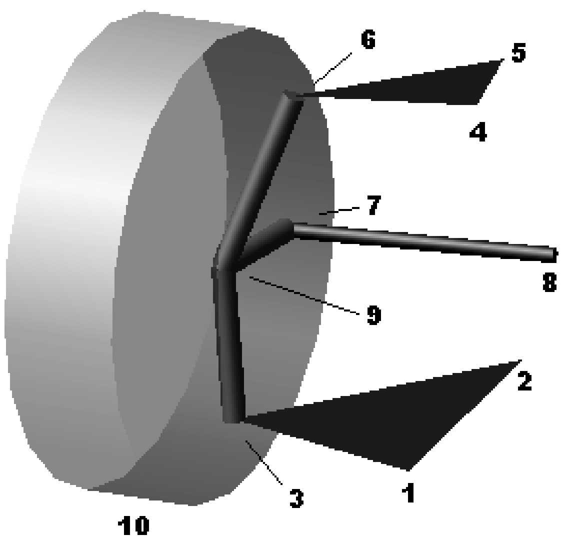

Figure 1. ADAMS model of SLA suspension with numbered hardpoints corresponding to Table 1 (right side shown).

In this example, the left outer tierod location (hardpoint) is changed in 3-D space. The coordinates of the outer tierod location, in italics in Table 1, are the factors in this experiment.

The output response tracked in this experiment is the change in toe angle as the suspension moves through its range of motion from jounce to rebound. Toe angle is the projected angle the wheel plane makes with the ground when viewed from above the vehicle. Toe-in is a positive number, and toe-out is a negative number. This measurement is important as exaggerated changes in toe angle result in aggressive tire wear.

In the traditional role of Design of Experiments in the product design process, the tierod variation represents a *design choice*—tierod lengths and shapes are changed because of performance or packaging considerations—as if the designer selects a new tierod size from the "catalog" with each iteration of the DOE. Due to the parameterized nature of the suspension model, any change in tierod length will cause corresponding resizing in neighboring parts to accommodate the new length. This suspension model is used to illustrate this case.

Table 1: Suspension Geometry Hardpoints

	Hardpoint Name	Location (x,y,z)*
1	Lower control arm, front attach point	67, 400, 180
2	Lower control arm, rear attach point	467, 450, 185
3	Lower control arm, outer attach point	267, 750, 130
4	Upper control arm, front attach point	367, 450, 555
5	Upper control arm, rear attach point	517, 490, 490
6	Upper control arm, outer attach point	307, 675, 555
7	*Tierod, outer attach point*	*417, 750, 330*
8	Tierod, inner attach point	467, 400, 330
9	Wheel center	267, 760, 330
10	Wheel patch	267, 760, 0
	*Right side; left side is symmetric about y=0	

However, the *robustness* of a particular design can be also be assessed with Design of Experiments, using statistical variations in tierod lengths and shapes due to manufacturing variability or tolerances. This approach can help determine which tolerances are most critical to maintain for a robust design. Notable characteristics of using Design of Experiments to assess robustness on a suspension model like the one shown in this section include:

- The tolerance of a hardpoint is used as a factor
- Differing tolerances can be specified on mating parts (e.g., suspension arm and subframe)
- Resizing of parts does not occur—the DOE can account for piece-to-piece variation
- The DOE mimics a "real-life" manufacturing process where parts are forced in place—it introduces pre-loads in bushings; it can be used to develop a shimming strategy

ADAMS/Insight uses Monte-Carlo analysis techniques to analyze the system behavior over an expected statistical distribution of parameter settings (perhaps based on prior experience or knowledge about manufacturing process variability or other influences). Such a statistical distribution input is called a Probability Density Function. The section, "Eleven position synthesis using a Robust Design approach" on page 5 includes a linkage model which has been subjected to a Design of Experiments utilizing the Monte-Carlo approach. Refer to Fig. 1 for an illustrated summary of this discussion.

For this suspension example, a prematurely or unevenly worn tire is considered a defect. By determining which suspension parameter settings yield a model which is least likely to exhibit significant toe angle change, the manufacturer can minimize the possibility of future tire wear. This relates to Six Sigma and Robust Design as shown schematically in Fig. 2.

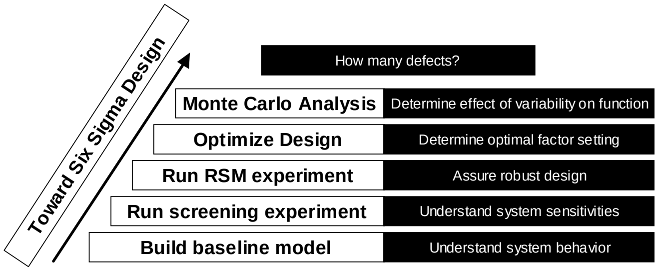

Figure 1. Relationship between Six Sigma, Robust Design, and Design of Experiments

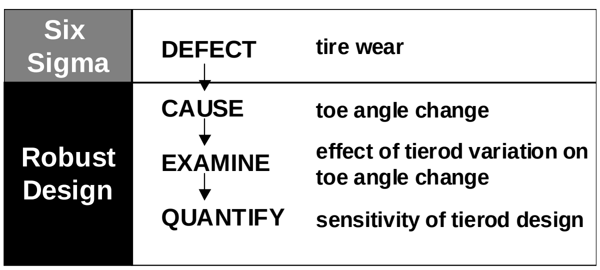

Figure 2. Relationship between Six Sigma and Robust Design

ADAMS/Insight Process

When the suspension model is imported into ADAMS/ Insight, a multi-step process is carried out to determine its performance with different tierod configurations:

1. Include Desired Factors and Responses. Select the factors to be included in the design matrix, and define parameters for the factors, such as nominal value, range, tolerance, ease of adjustment, and identifying information such as factor name and units. There are generally far more factors which ADAMS makes available for inclusion than may be necessary for a particular experiment.

The responses to be measured during the experiment must similarly be selected and properly identified for inclusion in the design matrix.

For this example, the included factors are the x, y, and z coordinate of the left tierod outboard connection, and the included responses are the right and left toe angles.

2. Setting Design Specifications. When the desired factors and responses are selected, an experiment design type can be chosen. An understanding of the various methods in Design of Experiments, such as screening versus response surface and full factorial coverage versus a reduction method, such as Box Behnken, is required and is beyond the scope of this paper. Consult reference [4] for complete details. ADAMS/ Insight provides many options for selecting an experiment type, and then automatically generates the Design Work Space (run matrix), which indicates the number of ADAMS simulations to be run, and the factor settings for each simulation. The chosen experiment design type dictates the values of the factor settings and the number of required simulations.

3. Running the Experiment. ADAMS/Insight automatically initiates the ADAMS simulations required to obtain the response data for the Design Work Space. When these simulations are completed, the response data is automatically filled in.

4. Fitting the Results. ADAMS/Insight fits the results to a polynomial or a response surface. The purpose of fitting results is to establish a statistically valid relationship between the factors and responses that were selected for the workspace matrix. Fitting results includes a multiple regression, and a number of standard statistical indicators of goodness-of-fit are provided for the user to evaluate.

5. Optimizing the Results. ADAMS/Insight permits both single-object and multi-object optimization. Single-object optimization involves trying to achieve a target for one scalar response; multi-object optimization involves more than one scalar response.

6. Publishing Results. ADAMS/Insight supports data export to HTML and SYLK files. Once saved, a browser or spreadsheet program, such as Excel, can be used to modify factors and see the effect on responses without performing full simulations. The estimated responses adjust to reflect the new factor values. In this example, only one of the responses, the left toe angle, reflects a change. This is because this ADAMS model is an independent suspension, in which the right tie rod is not coupled with the left tie rod. Therefore, the changes in the factor values in this experiment only affect the left side of the suspension. The Web page created by ADAMS/Insight provides simple functionality for varying the factor values and investigating how changes to them affect your responses. A pareto chart at the bottom of the Web page indicates the relative importance of the participating design factors in affecting the response metric.

It is clear from this data that alterations to the y (lateral) coordinate of the outboard tierod connection will make a significant change to the toe angle in this particular suspension. Therefore, this parameter must be closely controlled throughout design, component manufacturing, system assembly, and field maintenance to minimize toe angle in the interest of retarding tire wear. Please note that this suspension is greatly simplified and this conclusion is not to be generalized to any other independent rear suspension. Also note that many additional factors may contribute to toe angle change, and these would need to be considered in a more complete study.

The ADAMS model and related files for this suspension analysis are available at http://university.adams.com/asme for further study.

ELEVEN POSITION SYNTHESIS USING A ROBUST DESIGN APPROACH

Faced with the eleven position synthesis problem posed by the organizers of this symposium, the authors have chosen an alternative approach, which features the Robust Design techniques currently employed by ADAMS users in industry, rather than elaborate synthesis algorithms.

The challenge was to synthesize a linkage that would traverse a series of 11 points in the x-y plane, with an orientation specified at each point. The curve formed by these points, as well as the ADAMS model used here are shown in Fig. 3. The series of points are recorded in Table 2.

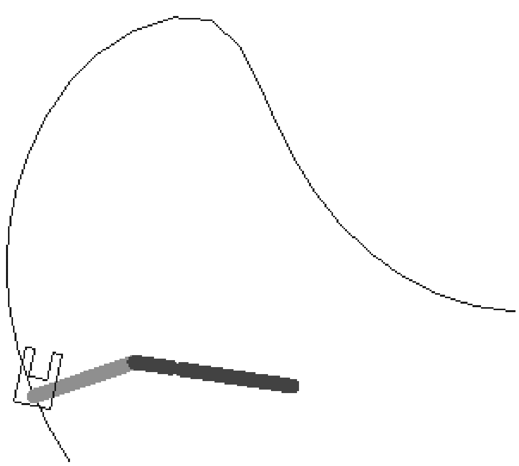

Figure 3. ADAMS model of the ASME linkage challenge problem

The linkage in this example was treated as if it were a large and heavy industrial robot, perhaps for used painting or fastening. The ADAMS model was constructed from two telescoping links, connected by a intermediate revolute joint. The linkage connects to ground by a revolute joint, and the end effector shown connects to the outboard link by a spherical joint. The robot has a mass of approximately 106 kg, and the initial length of the robot arms is each less than 1 meter. The motion along the desired path was directly specified using the General Motion function in ADAMS, which allows the user to specify displacement, velocity, and/or acceleration of all six degrees of freedom of a part in ADAMS.

Table 2: Design point locations and orientation for the ASME Linkage Challenge

	x	y	θ
1	-1.0000	-1.0000	90.0000
2	-1.2390	-0.5529	77.3621
3	-1.4204	0.3232	55.0347
4	-1.1668	1.2858	30.1974
5	-0.5657	1.8871	10.0210
6	-0.0293	1.9547	1.7120
7	0.2632	1.5598	10.0300
8	0.5679	0.9339	30.1974
9	1.0621	0.3645	55.0346
10	1.6311	0.0632	77.3620
11	2.0000	0.0000	90.0000

The Robust Design consideration is related to the installation of the robot on the plant floor. If the base joint is not installed precisely to the tolerances specified, will base joint torques be induced which cause the base to loosen or fail? A base joint failure is the product defect that was addressed through Robust Design and Six Sigma techniques, and the base joint location was considered a factor in the Design of Experiments study.

The torque magnitude produced on the base joint for the baseline simulation case is shown in Fig. 4. This measurement was considered the response for the Design of Experiments study.

Following the baseline simulation, a Monte Carlo simulation was performed on the linkage, with the following set of parameters:

- A normal distribution for the Probability Density Function of the variance of the base joint location in both the x and y directions was used.
- A production volume of 100 robots was used (100 simulations were performed).
- The tolerance on the base joint location was 5 cm.

ADAMS/Insight orchestrated the simulation of all 100 robots with varying base joint location.

Using the Six Sigma criteria, 49 of the 100 robots were judged to exceed criteria for failure, as they exhibited peak joint torques greater than 2 orders of magnitude larger than the baseline simulation. This is a subjective criterion, but clearly an objective criterion could be established as well.

The other 51 robots exhibited peak joint torques ranging from 5.7×10^5 to 6.0×10^5 N-m, which is within the range expected from the baseline analysis.

The ADAMS model and related files for this linkage analysis are available at http://university.adams.com/asme for further study.

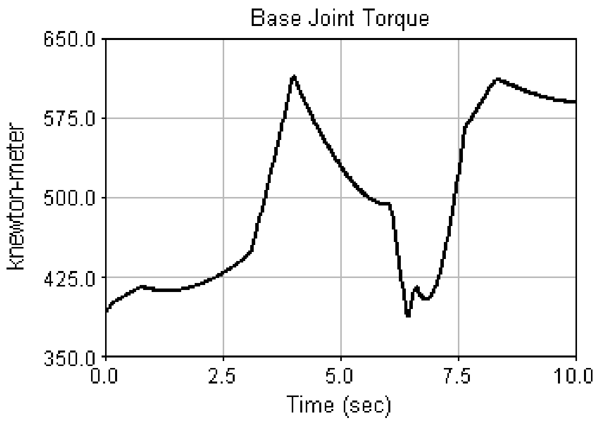

Figure 4. Baseline torque magnitude on robot base joint.

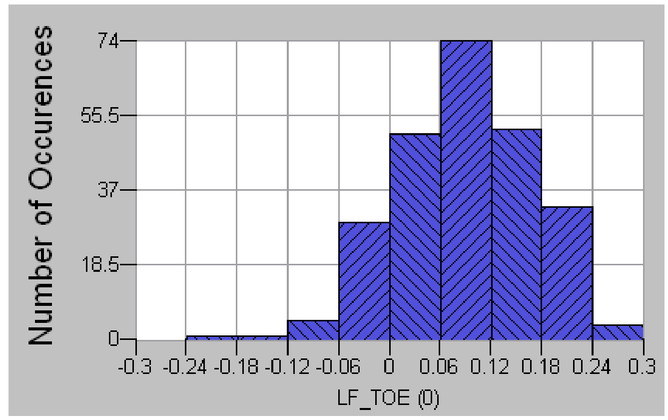

Figure 5. Suspension toe angle histogram from Monte Carlo analysis

Relating the robot design back to the suspension analysis in the main section of this paper, a Monte Carlo analysis of a suspension would be expected to produce results similar to those shown in Fig. 5. By examining the data at either extreme of the distribution, it is possible to determine the expected number of "failures" or unacceptable configurations of the suspension for a given production volume.

CONCLUSION

Over the last twenty-five years, mechanical system analysis, now known as Functional Virtual Prototyping, has evolved to a play a prominent role in product design. The automotive industry, as an enthusiastic adopter of the technology, has played a leading role in defining the direction in which the software has evolved. Mechanical Dynamics' ADAMS software is therefore reflective of the influence of the automotive and other major industries.

A great deal of automotive design is evolutionary. In the experience of Mechanical Dynamics, the automotive industry does not call upon Functional Virtual Prototyping to synthesize novel mechanisms. Rather, the technology is used to help the industry meet requirements for quality, as well as design targets for functional attributes such as ride, handling, durability, and vibration.

Using ADAMS/Insight to experiment with virtual prototypes helps increase the reliability of conclusions, get answers faster than trial-and-error or testing factors one at a time, improve understanding, and refine the performance of a mechanical system.

This paper demonstrated how a typical automotive design problem, an independent suspension, can be greatly influenced by Robust Design thinking—using design of experiments techniques on a functional virtual prototype to understand how to achieve the most effective balance between competing design parameters and performance metrics, and meet today's Six Sigma requirements for product quality.

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