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TAGUCHI METHODS IN ELECTRONICS—A CASE STUDY

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Information and Electronic Systems Laboratory
Science and Engineering Directorate

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13. ABSTRACT *(Maximum 200 words)*

A pilot project in Taguchi methods was completed using actual electronic hardware. The primary purpose was to familiarize engineers and managers with the theory and mechanics of doing a Taguchi experiment. The hardware selected was the National Launch System (NLS) electromechanical actuator (EMA) control electronics. This is a 25-kW motor controller. Actual preparation and test time was 3 to 4 weeks. Results were quite good since the predicted optimum set of component values also had the highest measured signal-to-noise ratio (S/N).

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Case Study Participants

This project was a group effort. The 10 members of the group were led by E.C. Smith, Branch Chief of the Control Electronics Branch, Information and Electronic Systems Laboratory. He selected the application and saw it to completion. Frank Nola, team leader for the Motors, Controls, and Servomechanisms team under Mr. Smith, helped with questions on circuit and motor design.

The Taguchi method class instructor, Jim Quinlan, is experienced in all aspects of the method and was particularly helpful in defining the problem and knowing what can be done. Mr. Quinlan has his own company, ITEQ International, Ltd., which deals with all aspects of total quality management (TQM).

Group members on Mr. Nola's team included Ralph Kissel, Taguchi method spokesman, data analyst, and report writer; David Howard, circuit designer; Justino Montenegro, circuit designer; Bill Jacobs, circuit designer; Ken House, laboratory assistant; and Dean Alhorn, experienced in the Taguchi method from recent Master's degree work.

Ms. Rae Ann Weir, of the Propulsion Laboratory, works on the Electromechanical Actuator project and provided battery power.

TECHNICAL MEMORANDUM

TAGUCHI METHODS IN ELECTRONICS—A CASE STUDY

INTRODUCTION

Total quality management (TQM) is becoming more important as a way to improve productivity. One of the technical aspects of TQM is a system called the Taguchi method. This is an optimization method that, with a few precautions, can reduce test effort by an order of magnitude over conventional techniques. The Taguchi method is specifically designed to minimize a products' sensitivity to uncontrollable system disturbances such as temperature, aging, voltage variations, etc., by simultaneously varying both design and disturbance parameters. The analysis produces an optimum set of design parameters.

A 3-day class on the Taguchi method was held at Marshall Space Flight Center (MSFC) in May 1991. A project was needed as a follow up after the class was over, and the motor controller was selected at that time. Exactly how to proceed was to be the subject of discussion for some months. It was not clear exactly what to measure, and design kept getting mixed with optimization. There was even some discussion about why the Taguchi method should be used at all.

TAGUCHI METHOD OVERVIEW

The Taguchi setup and analysis looks much like what one would see for a standard design of experiments problem. However, randomization is not required and is generally not even possible (with orthogonal arrays), although it is good when it can be done. This allows the most convenient test order to be used and also minimizes the number of tests that have to be made. For example, in this case there were 11 unknowns and just 12 component combinations to test. Even the number of runs for one combination can be minimized by combining noises properly.

Sets of special predefined arrays are used to determine the proper component value combinations for each test and also the proper noise levels to use, when those are part of the testing. Known component interactions will require a different array to be used than if all the components are acting independently. A standard orthogonal array mixes the noise (interactions, nonlinearities) throughout the results and tends to average it out. Adding known interactions reduces the experimental error but requires more testing to be done.

The basic idea of Taguchi testing is to define a signal-to-noise ratio (S/N in decibel (dB)) and maximize it.[1 2] The S/N is defined as in electricity but is more general than that. Signal is anything that is good or wanted, while noise is anything that is bad or unwanted.

Some interaction and nonlinearity can be present without significantly affecting the outcome. However, the optimum outcome must always be tested in a separate confirmation test to make sure that the predicted component set is in fact correct. Unexpected nonlinearities or interactions will cause the measured optimum to have a much lower S/N than expected. This means that the entire test has failed and must be rethought and redone.

Cost is usually not a consideration in Taguchi testing, except for the expense in actually performing the tests. The purpose is to optimize the current design, not build a new one. The optimized design is expected to improve reliability or lifetime to the extent that any cost involved is recovered many times over.

TAGUCHI METHOD OUTLINE

The following is an outline of the steps involved to run a Taguchi method experiment:

1. Understand the problem
2. Define the input/output (I/O) function
3. Choose control variables
4. Choose noise variables
5. Choose signal variable (if any)
6. Choose output(s) to measure
7. Select levels of everything
8. Choose best orthogonal array
9. Run the tests
10. Analyze the data
11. Confirm the results
12. Retest if necessary.

Each of these will be explained in more detail. Taking a class in Taguchi methods is highly recommended, especially around the time actual tests are being done.

Understand the Problem

With this method, almost anything can be optimized. Alternatives for the selected system can be evaluated very early in the design process. The most important concept to remember is that the method is designed to minimize deviations (noise) from the desired output (signal). Desired output is determined by the problem being solved, while noise is anything which interferes with that output. Optimizing the wrong output gives good answers to the wrong problem.

Define I/O Function

More thought probably goes into this than all the other parts combined because, while it sounds simple, it is the most difficult. Implicit in choosing an I/O function, often called the ideal function, is deciding whether the desired signal is to be zero, some average value, or a straight line function. There are others but these are the primary ones. Taguchi methods do not deal with anything more complicated than a straight line function. Each selection has a different S/N definition and different equations for calculating it. The function currently recommended most is the zero-point-proportional (ZPP) straight line through zero because it has been failing the least, i.e., it works almost every time.

To minimize a deviation requires that two values be stated: target value and actual value. Further, for ZPP, the target value is required to be a linear function through zero. ZPP also requires an input signal which leads one to think of an input as in a control system. No such signal was found for the motor controller. Other considerations such as rise time, settling time, spikes, switching, voltage versus current, equal intervals or not, time delays, etc., complicate the matter. The eventual decision in this case was to define the power supply voltage as the signal and to vary it as required, even though in actual use this voltage should be constant. It is not intuitive to define a signal in this way but the method works and may even require such a definition. With this definition, the measured voltage was targeted at the supply voltage, the measured voltage was zero when the supply voltage was zero, and any deviation from target could be measured and minimized by the analysis. It also happened that the troublesome overshoot was a deviation from this target voltage.

Choose Control Parameters

Control parameters may be dimensions, component values (resistor, capacitor, etc.), materials, and other parts of the design or environment that can be controlled even after the product is deployed. Even a wire length or a part being either in or out qualifies. Some parameters, i.e., temperature or load current, may be either a control parameter or noise parameter depending on whether control is maintained after deployment.

Choose Noise Factors

Noise factors may be environmental variables, load variables, power variations, etc., that can be controlled during testing but not afterwards (when deployed). Making the product insensitive to these variables by selecting control parameter values is the main purpose of the analysis, although control parameters will be selected to produce minimum deviation even without varying (or having) the noise factors. This is equivalent to having just one level of noise factor.

It has been found that only the major noise factors need to be used. Minimizing the effect of the major ones also reduces the effect of the lesser ones. While noise factors can be broken out and the effect of each one determined, this is not usually desired. All the noise effects are generally combined into two levels, N1 and N2. The N1 group consists of those factor levels that cause a negative deviation, while the N2 group levels produce a positive deviation. This is to produce the maximum difference between the effect of N1 and N2. Sometimes a preliminary test must be made to determine the direction of deviation when a noise factor is changed in order to properly combine the factors this way.

Choose Signal

The signal is the I-part of the I/O function. It needs to be easily controlled since it will be varied often during the tests. The signal, as in this case, may not be a signal in the usual sense. Power supply variation is generally thought of as noise rather than signal or input as used here. If the selected I/O is not linear, a signal will not even be used or considered. It should also be noted that a signal in one case can be noise in another case.

Output Measurement

The desired output is the O-part of the I/O function. The output must be measurable and reasonably repeatable over the period of testing considering variations in test setup, environment, and all the rest. Obtaining good results requires control of all factors during testing.

Proper instrumentation to collect the required measurements must be available before testing begins. Recording large amounts of data requires that a computer be included in the test for this purpose. Hard copy of all results should probably be required, not only to save the required data for checking, but also to go back for data that are later found to be desired or necessary. Any later change in requirements, however, will probably produce the need for data that were not recorded at all.

Select All Levels

Level selection has several considerations. One is to choose levels that are either standard or readily available. The nominal design levels may or may not be used. A two-level design can either have nominal (current) values for one level and values expected to improve the performance for the other level, or one level chosen below the nominal and the other above. A three-level design can use nominal values for the middle level and one level below and one above nominal. The three-level design does require considerably more test time.

Separating the level values is another issue. This requires some detailed knowledge of how the level values affect overall system performance. Changing a component by 1 percent, for example, may produce no noticeable effect. Sometimes even a 100-percent change would not be enough. These values have to be selected based on experience and perhaps some prior sensitivity analysis with larger changes being preferred to smaller ones. It may even be necessary to make one complete test and then do one or more iterations to home in on the optimum control parameters.

Choose Orthogonal Array

There are 18 "standard" arrays defined to handle most Taguchi test requirements.[3] They are orthogonal (each control factor being independent of the others) arrays and have interactions mixed in with the results in some way. Significant interactions are often known ahead of time, and these can be included explicitly as a separate column in the array. Some of the standard arrays have certain interactions already included but arrays can always be designed for special situations.

Taguchi says the most important characteristic of orthogonal arrays is that they can detect the presence of significant interactions and nonlinearities by causing the confirmation test to fail. The test fails when the measured S/N value is much different than expected and not close to the predicted optimum value. Any product failing this test should not be turned loose because it would likely fail soon on its own anyway.

On the other hand, the procedure is quite tolerant of these interactions and nonlinearities. Some of this is always present, and, if the confirmation test looks reasonable, there is little cause for concern.

The control parameter orthogonal array is called the inner array. It is chosen so that it has the proper number and type of parameters (and interactions, if any), has the correct number of levels for each one, and has the fewest number of tests (control parameter combinations) to run.

The noise factor orthogonal array is called the outer array. It is often a two-variable array, and sometimes is not even used (inherent data noise, never controlled, is all there would be).

The signal factor is usually chosen as three levels because two levels do not give a good enough estimate, and more than three costs more than it is worth.

Performing the Test

One freedom available here that is not normally permitted in running a standard design of experiments test is that the testing can be done in any order. Some parameter values are harder to change than others, so these are assigned to columns where changes occur least often. The testing order can later be changed without being too concerned about affecting the outcome. In an orthogonal array, testing is decidedly nonrandom. Results are still valid even if a control factor is omitted because the array remains orthogonal. What is not permissible is to redesign the test before it is finished. All tests must then be redone.

Analysis

Analysis is typically done by spreadsheet. Setup (but maybe not data entry) should take less than 2 hours since the equations are not complicated. The equations are standardized for the type analysis being done. A software package specifically for analyzing Taguchi test data is sold by American Supplier Institute, Inc. (ASI) of Dearborn, MI. This package has a user interface in Taguchi terms and does some helpful calculations but it is somewhat limited in the size problem it can handle compared to a spreadsheet. It is also more expensive than a spreadsheet. In this case, both analyses were used and checked against each other.

The analysis results in an optimum set of control parameters that are checked by the confirmation test. There may need to be further tests and analyses done if it is suspected that the true optimum has not yet been reached. One engineer commented that doing this many tests should make the solution obvious whether the analysis worked or not.

Results can be presented as S/N plots, spreadsheet tabulations, or in response tables. Response tables are part of the analysis, and this is where the optimum set of values is calculated. The response table takes each control parameter in turn and gives the average S/N for level 1, for level 2, etc., for all test combinations in which that level appeared. The orthogonal design permits this to be done. Then the highest S/N is chosen for each parameter. This is the optimum parameter set.

The Confirmation Test

This test is a test of one combination (the optimum), made like all the others, except that this combination had probably never been tried before. The expected S/N value is calculated ahead of time using the optimum values. The S/N using the measured data is then calculated and compared with the expected value. Although judgment determines whether the test failed based on how repeatable and sensitive the other S/N have been when components changed, this is fairly obvious. A confirmation value better than has been measured before is indicative of a successful test, otherwise some checking is in order. Some have tried using a two-sigma confidence interval on the predicted value to determine whether the test failed, but this has not worked well in practice.

TEST DATA AND CALCULATIONS

Figure 1 shows the circuit that was actually used for the experiment. It was chosen because it was rather small and because it had a potential problem. A large amount of voltage overshoot (noise) was always present across the load, and this could overstress the connected components, especially the IGBT. Therefore, this was chosen as the point to measure and minimize the noise.

Figure 2 shows the approximate beginning (BEFORE) overshoot along with the approximate optimized (AFTER) overshoot. There is some question about when the BEFORE is defined because some component values were being changed to improve circuit performance even before the Taguchi method was applied. The AFTER harmonics make it somewhat difficult to get an accurate reading. In any case, the improvement is obvious.

Figure 3 shows the $L_{12}(2^{11})$ array that was chosen for this problem. This is one of the standard arrays. The 12 is how many test combinations are to be used, the 2 means there are 2 levels for all the control parameters, and the 11 means there are 11 control parameters. Interactions in this array are uniformly distributed to all the columns (variables). It is a very efficient design and was large enough to handle all our variables.

Figure 4 shows the actual arrays with all component values in place. Levels were selected based primarily on experience. The outer array is laid out fully as the N1 and N2 columns. This is where the data will go. There is an N1 and N2 for each component combination and for each signal (M) level.

Figure 5 shows how the noise factors were grouped in either N1 or N2 columns depending on the expected effect of each on the noise. The noise variable, I_L, requires that the input, VIN, be adjusted to maintain the proper load current before every measurement is made. This caused the simulation time to increase substantially, as explained below.

Figure 6 shows the four points on a nominal load voltage plot that need to be recorded for each test condition. The first point alone might be enough but adding the others tends to reward faster settling time and also adds data for extra degrees of freedom. Since temperature is the most difficult parameter to change, requiring use of an environmental chamber, all tests were run at one (room) temperature, and then they were all run at the second temperature. Furthermore, since the noise factors were grouped, changing temperature also required changing the load inductor and the input current.

Figure 7 is the actual data for all tests as entered into the spreadsheet. For every data slot in figure 4, there are actually four values recorded. These are processed by the spreadsheet using the equations below. The columns containing zeros were kept in reserve for a time-dependent voltage value, but mixed results occurred whenever these values were tried. Rise time or time delay could be included in the optimization this way.

The equations used for the ZPP analysis (true signals known) are given below:[4]

$$S_T = \Sigma\,(d^2) = SS_{tot}$$

$$r = r_o\,(M_1{}^2 + M_2{}^2 + M_3{}^2)$$

$$b = (1/r)\,(M_1Y_1 + M_2Y_2 + M_3Y_3)$$

$$S_b = (1/r)\,(M_1Y_1 + M_2Y_2 + M_3Y_3)^2$$

$$V_e = (S_T - S_b)/(kr_o - 1)$$

$$S_n \text{ dB} = 10 \log\,((1/r)\,(S_b - V_e)/V_e)$$

$$S_b \text{ dB} = 10 \log\,(S_b)$$

$$d = r_o \text{ points}$$

$$r_o = \text{number of readings at } M_i$$

$$d.f. = kr_o\,,\ k = 3$$

$$Y_i = \Sigma(d)$$

S_n dB is the S/N value used to find the optimum set of control parameters, while S_b dB is used to find which control parameter to adjust if changing to the optimum settings produces a gain (slope) error. The component to adjust is the one that changes the gain the most and the S/N the least.

Figure 8 is the spreadsheet analysis for this experiment. Of primary interest is the S_n dB column. This is the calculated S/N and being negative is common. The relative magnitudes are what is important, even though the total range in this case is only about 6 db. The S_b dB column is another S/N that is used to determine gain sensitivity, but was not used here, and the b column shows the gain error (ideal gain = 1), but is of little concern here.

Figure 9 is the S_n response table showing not only which component makes the most difference but also by how much. Looking at the difference column shows that R101 has the most effect, and level 2 should be used. Next come the diodes which should be in the circuit (level 1), etc. Four or five components would not matter. The BEST column gives the complete optimum set.

Figure 10 shows the S/N predicted by using the optimum set and also by using the confirmation test data. The calculated S_n from these data is seen to be not only close to the predicted value but also higher than any previous S_n value. This experiment has confirmed very well.

SIMULATION

This circuit was simulated (using Pspice) to a limited extent but not nearly as much as needed to draw any helpful conclusions for the optimization. Simulation should be done in parallel with the testing so synergism can occur. The voltage values needed for this problem require that a transient analysis be done, and this can be very time consuming, with nonconvergence being a common occurrence. This particular circuit required that several simulations be made just to set the load current before any data could even be recorded. In the actual hardware, this just required a few seconds to set a potentiometer. Simulation also requires component models, some of which are difficult to define because the components are new (IGBT in particular). Once the simulation circuit is defined, considerable tuning of the simulation is needed to get agreement between hardware and simulation. Only then can the simulation be expected to generate believable data on its own.

Once a simulation is running, however, it can show results that are difficult or impossible to get from the hardware, such as power, currents, some calculated parameters, or results at a different temperature. In many cases, simulation results can be much less expensive to obtain. Problems may be worked out so that the simulation produces results much faster than hardware. Simulation and hardware normally work together to produce a better product.

CONCLUSIONS

The optimum S/N was slightly better than any test seen before. Comparing the BEFORE and AFTER plots shows an improvement of about 3:1 based on targeting 150 V, starting with 150 V overshoot and ending with 50 V overshoot. This was a successful test to demonstrate the capabilities of the Taguchi method. It is a methodical procedure to improve the robustness of, in this case, an electronic circuit.

FURTHER CONSIDERATIONS

Another test of the size used here should take less than 1 week to finish. Setup for instrumentation, making components easier to change and making personnel available, could extend this somewhat.

Technicians could perform the test but might not realize when something was going wrong. Engineers tended to view this testing as a rather mechanical, cookbook kind of task requiring little use of their engineering ability once testing actually started. They also thought they could probably design a better circuit than would result from the Taguchi testing.

A Taguchi test should only be done after a reasonable design is available. Research projects often do not have finished designs. Any major design change invalidates previous optimization results.

Someone has to know the Taguchi method to at least act as a consultant for the many situations that will occur. In this case, the original class instructor was usually available to help.

Management must support this work since it is still rather new in most circles, and manpower and equipment must be dedicated to the task. Trying to change the way something is done has its own set of problems.

Taguchi methods have been refined to the point that they work most of the time but not every time. With some thought, changes can be made which will solve the problem. An interaction may have to be added to the inner array, some necessary factor may have been entirely omitted, or a different ideal function may be required.

Further work could be done by optimizing other parts of the same controller (this was only a small part of the circuit) and then finally combining these parts, or simplified functional equivalents, into one large problem. Justification for this work involves assessing whether resources are available and whether the result would be significantly better than already exists.

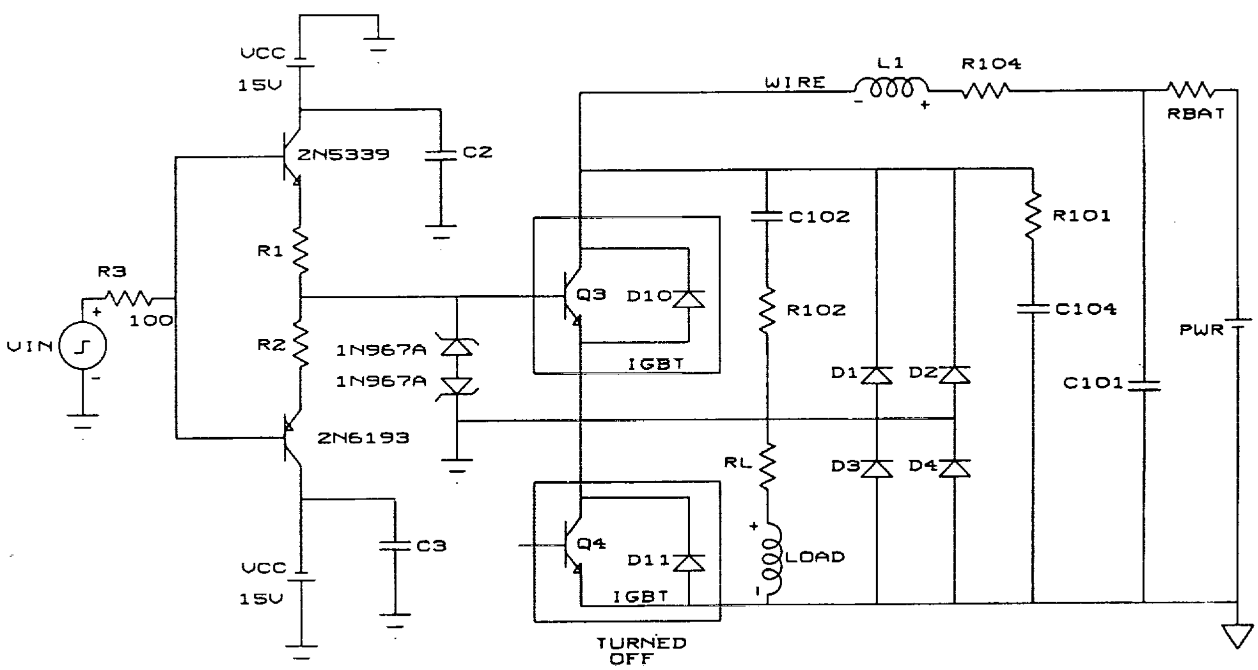

Figure 1. Motor controller test circuit.

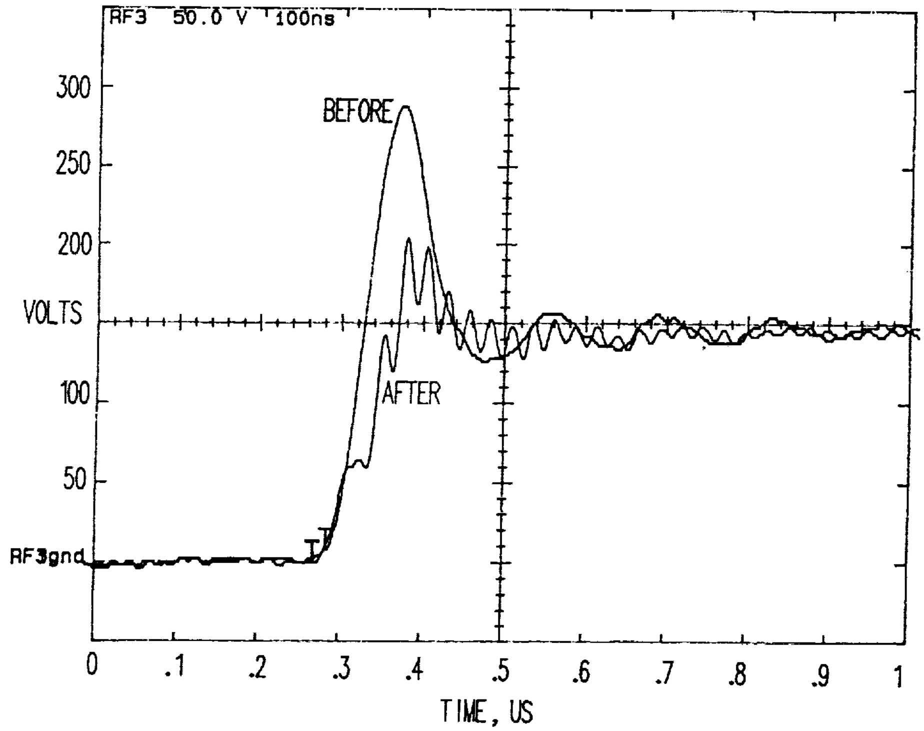

Figure 2. Voltage transients for TVC motor controller electronics.

L12(2^11)

	CONTROL FACTORS										
No.	1	2	3	4	5	6	7	8	9	10	11
1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	2	2	2	2	2	2
3	1	1	2	2	2	1	1	1	2	2	2
4	1	2	1	2	2	1	2	2	1	1	2
5	1	2	2	1	2	2	1	2	1	2	1
6	1	2	2	2	1	2	2	1	2	1	1
7	2	1	2	2	1	1	2	2	1	2	1
8	2	1	2	1	2	2	2	1	1	1	2
9	2	1	1	2	2	2	1	2	2	1	1
10	2	2	2	1	1	1	1	2	2	1	2
11	2	2	1	2	1	2	1	1	1	2	2
12	2	2	1	1	2	1	2	1	2	2	1

Figure 3. Textbook array.

	CONTROL FACTORS										SIGNAL					
											M1=50V		M2=100V		M3=150V	
TEST	C2/C3	Q1	Q2	C102	R102	R101	C104	C101	D1-4	WIRE	R1/R2	N1	N2	N1	N2	N1	N2
1	44 uF	5339	6193	2000 pF	30 ohms	9 ohms	0.1 uF	2400 uF	IN	4 inches	10 ohms						
2	44	5339	6193	2000	30	6	0.2	5500	OUT	8	15						
3	44	5339	3868	1000	10	9	0.1	2400	OUT	8	15						
4	44	4150	6193	1000	10	9	0.2	5500	IN	4	15			DATA ARRAY			
5	44	4150	3868	2000	10	6	0.1	5500	IN	8	10						
6	44	4150	3868	1000	30	6	0.2	2400	OUT	4	10						
7	22	5339	3868	1000	30	9	0.2	5500	IN	8	10						
8	22	5339	3868	2000	10	6	0.2	2400	IN	4	15						
9	22	5339	6193	1000	10	6	0.1	5500	OUT	4	10						
10	22	4150	3868	2000	30	9	0.1	5500	OUT	4	15						
11	22	4150	6193	1000	30	6	0.1	2400	IN	8	15						
12	22	4150	6193	2000	10	9	0.2	2400	OUT	8	10						

Figure 4. Experiment design.

	LOW SPIKE	HIGH SPIKE
NOISE FACTOR	N1	N2
TEMPERATURE	25 DEG C	50 DEG C
LOAD	L1	L2
LOAD CURRENT	50 A	100 A

L1=0.00178 H, 0.025 OHMS
L2=0.00243 H, 0.077 OHMS

Figure 5. Noise levels.

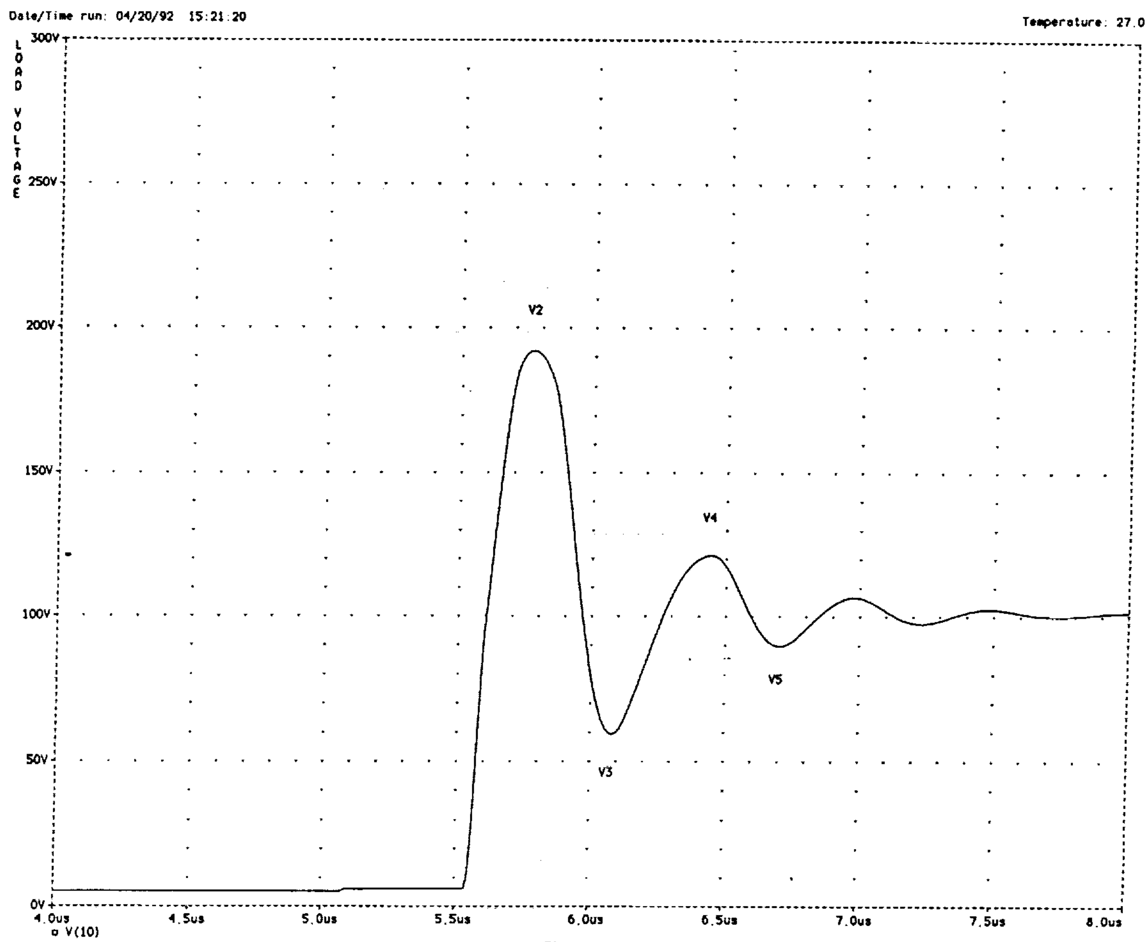

Figure 6. Nominal load voltage plot.

	ro=8		50					100					150		
N1	0.0	66.4	42.0	49.4	42.8	0.0	176.0	63.0	106.0	77.0	0.0	298.0	99.0	180.0	122.0
N2	0.0	69.6	34.8	44.4	41.2	0.0	146.0	78.0	94.0	86.0	0.0	257.0	104.0	158.0	126.0
N1	0.0	73.6	44.8	46.4	42.8	0.0	167.0	87.0	99.0	87.0	0.0	270.0	132.0	150.0	134.0
N2	0.0	77.6	42.4	42.4	42.4	0.0	153.0	91.0	93.0	92.0	0.0	236.0	146.0	143.0	144.0
N1	0.0	96.4	36.0	49.2	39.2	0.0	224.0	80.0	108.0	82.0	0.0	344.0	122.0	162.0	130.0
N2	0.0	92.8	39.6	44.4	44.0	0.0	179.0	87.0	91.0	91.0	0.0	268.0	134.0	140.0	146.0
N1	0.0	64.6	37.8	46.2	40.8	0.0	162.4	69.6	103.2	85.6	0.0	280.0	112.0	170.0	132.0
N2	0.0	64.4	34.4	42.4	40.0	0.0	142.4	78.4	96.0	88.0	0.0	222.0	116.0	144.0	128.0
N1	0.0	57.6	43.0	47.2	43.2	0.0	137.6	85.6	99.2	89.6	0.0	230.0	118.0	160.0	134.0
N2	0.0	57.6	41.6	43.6	42.8	0.0	112.0	88.0	96.0	92.0	0.0	200.0	141.0	156.0	147.0
N1	0.0	88.8	39.2	46.0	39.2	0.0	184.0	78.0	98.0	83.0	0.0	317.0	128.0	154.0	136.0
N2	0.0	90.0	43.6	45.2	44.4	0.0	164.0	90.0	94.0	93.2	0.0	244.0	138.0	144.0	142.0
N1	0.0	64.4	39.6	48.0	40.8	0.0	156.0	78.8	101.6	89.6	0.0	273.0	103.0	165.0	127.0
N2	0.0	62.8	38.4	42.0	42.0	0.0	126.0	87.6	90.8	90.0	0.0	227.0	125.0	153.0	139.0
N1	0.0	60.2	39.4	45.8	42.6	0.0	153.2	75.2	99.2	84.8	0.0	250.0	110.0	161.0	128.0
N2	0.0	63.5	38.0	42.5	41.2	0.0	124.0	84.0	94.4	90.4	0.0	226.0	122.0	148.0	132.0
N1	0.0	90.4	41.6	48.0	40.8	0.0	186.0	84.0	100.0	86.0	0.0	318.0	130.0	156.0	136.0
N2	0.0	88.0	44.0	44.8	44.0	0.0	164.0	90.0	92.0	92.0	0.0	240.0	138.0	144.0	141.0
N1	0.0	96.0	35.2	50.4	39.2	0.0	214.0	76.0	104.0	80.0	0.0	352.0	122.0	166.0	130.0
N2	0.0	88.8	36.0	42.4	41.6	0.0	168.0	84.0	92.0	91.0	0.0	250.0	128.0	140.0	139.0
N1	0.0	71.6	41.4	47.6	42.6	0.0	145.6	81.6	102.0	89.2	0.0	252.0	120.0	168.0	132.0
N2	0.0	59.6	42.6	44.0	42.0	0.0	116.0	90.4	94.4	92.8	0.0	198.0	138.0	146.0	142.0
N1	0.0	97.2	37.6	49.6	40.0	0.0	210.0	78.0	106.0	84.0	0.0	342.0	120.0	160.0	132.0
N2	0.0	96.8	42.4	46.4	45.6	0.0	188.0	88.0	94.0	93.0	0.0	286.0	140.0	148.0	144.0
	Tx	V2	V3	V4	V5	Tx	V2	V3	V4	V5	Tx	V2	V3	V4	V5

Figure 7. Spreadsheet data.

T	r	Sum d SQ	ST	S MiYi	Sb	Ve	Sn db	Sb db	b
		208444							
2560.6	280000	171061	379505	303730	329471	2175.39	-32.6976	55.1782	1.0848
		195017							
2636.4	280000	178415	373432	310770	344921	1239.58	-30.0428	55.3772	1.1099
		265874							
2829.6	280000	200955	466830	333180	396460	3059.53	-33.3798	55.9820	1.1899
		195865							
2500.2	280000	151973	347837	296690	314375	1454.89	-31.1456	54.9745	1.0596
		163771							
2462.6	280000	152575	316346	291730	303951	538.89	-26.9662	54.8280	1.0419
		228593							
2723.6	280000	186014	414606	320690	367293	2057.10	-31.9784	55.6501	1.1453
		187072							
2510.4	280000	158725	345797	297740	316604	1269.27	-30.5194	55.0052	1.0634
		172151							
2455.4	280000	153783	325934	290730	301871	1046.22	-29.8847	54.7982	1.0383
		233775							
2738.6	280000	182808	416583	321930	370139	2019.32	-31.8637	55.6836	1.1498
		266564							
2765.6	280000	182540	449104	326430	380559	2980.20	-33.4440	55.8042	1.1658
		180692							
2499.4	280000	147946	328638	295170	311162	759.83	-28.3595	54.9299	1.0542
		257786							
2868.6	280000	220009	477795	337680	407242	3067.52	-33.2738	56.0985	1.2060

Figure 8. Analysis calculations.

Sn db RESPONSE TABLE					
NAME	FACTOR	LEV 1	LEV2	DIFF	BEST
C2/C3	A	-31.0351	-31.2242	0.1891	44uf
Q1	B	-31.3980	-30.8612	0.5368	4150
Q2	C	-31.2305	-31.0287	0.2017	3868
C102	D	-31.0515	-31.2077	0.1562	2000pf
R102	E	-31.1736	-31.0856	0.0880	10 ohms
R101	F	-32.4100	-29.8492	2.5608	6 ohms
C104	G	-31.1185	-31.1408	0.0223	0.1 uf
C101	H	-31.5956	-30.6636	0.9320	5500 uf
D1-4	I	-29.9288	-32.3304	2.4016	IN
WIRE	J	-31.8356	-30.4236	1.4121	8 in
R1/R2	K	-31.2165	-31.0427	0.1738	15 ohms

Figure 9. Reponse table.

TEST	V2	V3	V4	V5
X.50.N1	62.4	45.6	52.0	47.2
X.100.N1	133.6	92.8	103.2	97.6
X.150.N1	220.0	134.0	162.0	144.0
X.50.N2	70.0	41.8	44.8	43.6
X.100.N2	142.8	85.2	97.2	89.2
X.150.N2	214.0	130.0	144.0	146.0

PREDICTED OPTIMUM S/N = -26.79 db
MEASURED OPTIMUM S/N = -26.88 db

Figure 10. Confirmation data.

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4. Class material supplied by American Supplier Institute, Inc. (ASI), 1990, from class in May 1991.

APPROVAL

TAGUCHI METHODS IN ELECTRONICS—A CASE STUDY

By R. Kissel

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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