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PASS/FAIL FUNCTIONAL TESTING AND ASSOCIATED TEST COVERAGE

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Key Words

Factorial experiments; Design of experiments; Statistical methods; Problem determination; Logic testing; Software testing; Microcode testing; Functional testing.

Introduction

Consider the situation where a product will be "put together" (i.e., configured) in many different ways by a customer. Because of possible design flaws, an inhouse test of possible combinations is of interest to discover problems. If the number of configuration possibilities is not large, a test person might simply evaluate all possible combinations to assess whether there are any design problems. However, in some situations an extremely large number of combinational possibilities precludes the possibility of testing all combinations efficiently.

This article describes a test strategy for those situations when the number of combinational possibilities is too large to test one by one. This proposed test strategy delineates a small subset of test configurations which identify the types of problems that are found in many situations, thus allowing for maximal coverage of possible problems with the fewest number of tests.

An example which we will return to again involves the electromagnetic interference (EMI) emissions of a product. Compliance to government specifications is important since noncompliance can result in legal actions by the Federal Communication Commission (FCC). However, each EMI test setup and measurement can be very time consuming and, therefore, to test all possible configurations of a complex system can be an impossible task.

To illustrate the type of EMI problems that the proposed strategy will capture, consider that (unknown to the experimenter) a new computer design emits unacceptable high EMI levels only when a certain type of display monitor is used in conjunction with a power supply that was manufactured by a certain vendor that had an optional "long size" cable.

In lieu of testing all possible combinations, an EMI test strategy that evaluates factors one-at-a-time would probably not detect this type of combinational problem. A nonstructural test alternative that evaluates a few common "typical configurations" might also miss important factor considerations because they are "not typical." In addition, the nonstructural test approach does not calculate test coverage at the completion of a test.

The test strategy discussed here addresses the efficient identification of circumstances where combinational problems exist. It should be emphasized that this approach focuses on the quick identification of problems as they are often defined. For example, a "group size" of three factor levels (i.e., display monitor type, power supply vendor, and cable length) caused a combinational problem in the above illustration. The example problem discussed later illustrates a simple basic test design strategy where there is a high probability of detection of the above design problem while executing only a minimal number of test scenarios. The example also addresses a measure for the *test coverage* that is achieved when using such a test strategy.

Test Approach

Fractional factorial design matrices usually assess continuous response outputs as a function of factor level considerations (see references for more information). However, there are instances when it is more appropriate to determine a *logic pass/fail* (binary) result that will *always* occur relative to machine function or configuration. This article shows how factorial design matrices can also be used to give an efficient test strategy for such a *pass/fail functional test* evaluation (1,2).

With this methodology, test trials from a fractional factorial design are used to define configurations and/or experimental conditions, while *test coverage* is used to describe the percentage of all possible combinations of the factor levels tested (c) for various group sizes (g). In the above EMI problem, a group size of three factors was identified (i.e., display type, power supply manufacturer, and power supply cable length). The example which follows shows how a test coverage of 90% can be expected for a group size of three given a logic pass/fail output consideration of seven two-level factors in only eight test trials.

The desired output from a factorial design matrix using the proposed test strategy is that all experimental trial conditions pass. The percent coverage for the test is determined in Figure 1. It should be noted, however, that whenever a trial fails there may be no statistical analysis technique which would indicate the source of the problem. If additional engineering analyses do not identify the problem source, additional trials can be added to assist the experimenter in determining the cause of failure (reference search pattern strategy in Ref. 2).

The percentage test coverage c that is possible from a factorial designed experiment where f two-level factors are assessed in T trials is:

$$c(f) = \frac{T}{2^f} \times 100 \qquad c(f) \leqslant 100\% \tag{1}$$

This means, for example, that if $T = 32$, the maximum number of two-level factors yielding complete coverage ($c = 100\%$) is $f = 5$.

Besides the total coverage of the experiment, it would be interesting to know the coverage of a particular subclass (or group) of g two-level factors chosen out

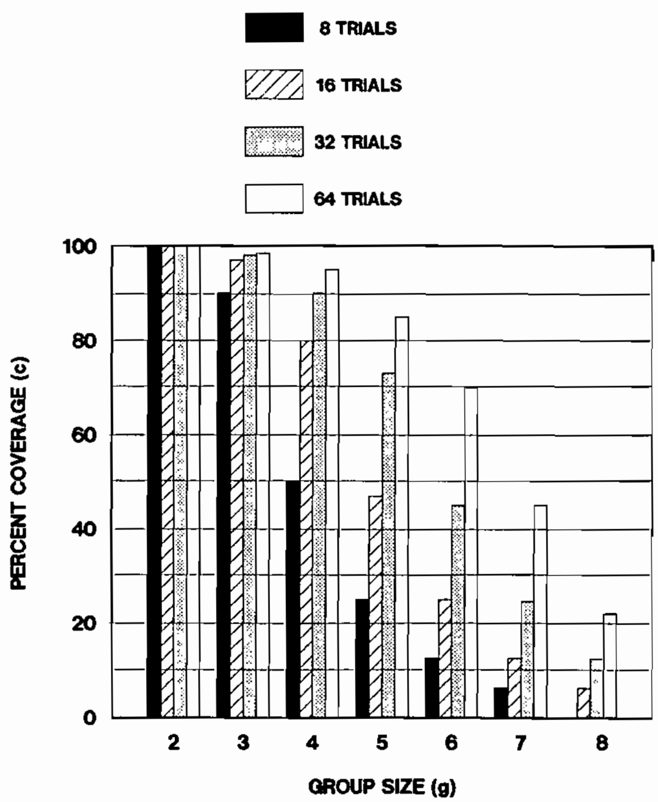

Figure 1. Test matrix coverage (2).

of the total f factors that comprise the experiment under consideration. Theoretically, Eq. (1) is still valid if g replaced f, but for a generic group of g factors the factorial matrix is not guaranteed against pattern repetitions. Therefore we expect to have

$$c(g) \leqslant \frac{T}{2^g} \times 100 \qquad g \leqslant T - 1 \tag{2}$$

This relationship gives us a theoretical maximum coverage value in a very general case.

A computer program was written by one of the authors (Angelo Aloia) to calculate the mean percent coverage of all the possible groups of g factors for f factors for a representative sample of fractional factorial design matrices containing 2^n trials, where $n = 3$, 4, 5, and 6 (2–7). Results from this study indicate that there is only a slight variation in the value of c as a function of f, which, when ignored, graphically yields Figure 1. Note, in lieu of using a computer program to manually observe and calculate the observed coverage, the aliasing structure could have been examined to determine this coverage.

The number of P possible g groups of factors is determined by the equation

$$P = \binom{f}{g} = \frac{f!}{g!\,(f-g)!} \tag{3}$$

The N total number of possible combinations of the two-level factors then becomes

$$N = 2^g \binom{f}{g} \tag{4}$$

The value c determined from Figure 1 is the test percent coverage of the N possible combinations of the factor levels.

The following procedure and example considers only two-level factors. A later section addresses other test scenarios.

Suggested Implementation Procedure

1. List the number of two-level factors (f).
2. Determine the minimum number of trials (T) (i.e., 8, 16, 32, or 64 trials) that is at least one larger than the number of factors. Higher test coverage can be obtained by using a factorial design that has more trials.
3. Choose a factorial design matrix from one of the noted references. Use Figure 1 to determine the test case percent coverage (c) for 3, 4, 5, 6, . . . two-level group sizes (g) with the number of trials (T).

4. Determine the number of possibilities for each group size (g) consideration using Eq. (4).
5. Tabulate the percent coverage with possible combinational effects to understand better the effectiveness of the test.

Example

Given a logic pass/fail response that has the following seven factors (f) and associated two-level assignments, determine the minimum number of test trials and test coverage that is obtainable with this design. (Note, a similar approach can be applied to the test situation where many more factors are involved. For example, 63 two-level factors could be assessed in a 64 trial design.)

FACTOR DESIGNATION	COLUMN LEVEL (−)	(+)
A	Display type X	Display type Y
B	Memory Size—Small	Memory Size—Large
C	Power Supply Vendor X	Power Supply Vendor Y
D	Power Cable length—short	Power Cable length—long
E	Printer type X	Printer type Y
F	Hardfile size—small	Hardfile size—large
G	Modem—yes	Modem—no

Using the above procedure, this test can be performed using eight trials. A design matrix for this test is

Trial No.	A	B	C	D	E	F	G
1	+	−	−	+	−	+	+
2	+	+	−	−	+	−	+
3	+	+	+	−	−	+	−
4	−	+	+	+	−	−	+
5	+	−	+	+	+	−	−
6	−	+	−	+	+	+	−
7	−	−	+	−	+	+	+
8	−	−	−	−	−	−	−

From Figure 1 and Eq. (4) it can be determined that

	NUMBER OF GROUPS (g)					
	2	3	4	5	6	7
Percentage Coverage (c)	100[a]	90	50	25	12	6
Number of Possible Combinations (N)	84	280[b]	560	672	448	128

[a]Example coverage statement: 100% coverage of two combinations of the seven two-level factors
[b]Example calculation

$$f = 7 \quad g = 3$$

$$\binom{f}{g} = \binom{7}{3} = \frac{7!}{3!\,(7-3)!} = 35$$

hence,

$$N = 2^3 \binom{7}{3} = 8(35) = 280$$

Note, with only eight trials there is 90% coverage for a group size of three, which contains 280 possibilities! If this is not considered to be satisfactory test coverage, Figure 1 can be consulted to visualize the increase in coverage that will be obtained if the number of factorial experimental trials is doubled to sixteen.

To illustrate the type of problem that this test would be able to detect, consider the EMI example failure condition (unknown prior to the test evaluation)

Display type X:	$A = -$
Power supply vendor Y:	$C = +$
Power supply cable length—long:	$D = +$

This combination of factor levels is noted to be contained in trial number 4; hence, trial 4 (in this case) would be the only test trial to "fail." As noted earlier, an experimenter would not know from the pass/fail information of the trials (i.e., trial four was the only trial that failed) what specifically caused the failure (i.e., the ACD combination of $- + +$ caused the failure). This information cannot be deduced since many combinations of factor levels could have caused the problem; however, with this test strategy, the tester was able to identify that a problem exists with a minimal number of test case scenarios. For the experimenter to determine the root cause of failure, a simple technical investigation may be the only additional work that is necessary. If the cause cannot be determined from such an investigation, additional trial patterns may be added to search for the root cause (2).

Factor Levels Greater Than Two

Two-level factors are generally desirable in a factorial experiment; however, factorial design matrices that contain levels greater than two can still be used to efficiently detect the above type of functional problems. If there are no design matrices available to describe the desired number of factor levels of interest, a two-level factorial matrix design can be used to create a design matrix. To exemplify a "quick and dirty" procedure for the type of problem discussed in this paper consider a four-level factor where two columns from the two-level input matrices are used to describe the four levels (i.e., $- -$, $- +$, $+ -$, or $+ +$).

For this multilevel experiment situation, the previous procedure using Figure 1 could be used with some modification. However, in general, when there are factors with a different number of levels it seems more applicable to randomly choose many different configurations of group size and examine whether these configurations were tested. The test percent of coverage (c) could then be calculated and plotted versus group size (g) to give a generalized picture of the coverage for the particular test.

Development of Figure 1

Two-level factorial design matrix alternatives are described in Refs. 2–7. Traditionally, a design matrix with two-factor interactions aliased with main effects is defined as a resolution III experiment design. A saturated resolution III design is where the number of two-level factors is one smaller than the number of trials. The saturated design matrices from the sources noted above are equivalent for 8, 16, 32, and 64 two-level designs. Figure 1 was generated from saturated designs of these matrices.

A computer study using resolution III designs indicated that a reduction in the number of factors improved the coverage only slightly. Therefore, "percent coverage" is considered dependent only on the number of two-level factor groups considered.

The coverage of a particular group of g factors is after either 100% or 50% for 2^n trial designs. Instead of arbitrarily assigning factors, an experimenter may wish to make assignments such that factor combinational considerations thought to be important have 100% test coverage. Combinational considerations should avoid those factors that are identity elements (3,5,7) or a multiple of identity elements of the design matrix.

Conclusions

Obviously it is important when using a factorial test matrix strategy not to exclude factors or factor levels that are important relative to the response of interest. A major advantage of the above test strategy is that it allows for brainstorming techniques to choose the factors and factor levels and minimizes the risk of missing variables important to the response of interest.

It is often impossible to test all combinations of factor levels because of the potentially staggering number of combinational possibilities. However, by determining the number of factor groupings that realistically should be assessed and then testing the combinations of factor levels within a factorial design structure, an "impossible" situation can become quite manageable. Most importantly, this strategy allows for reporting the test coverage effectiveness as well.

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