Environmental stress screening equipment: search, evaluation, design, experimentation

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In 1993, a series of new programs were bid by United Defense Limited Parnership (UDLP), formerly FMC, whose prime government customer insisted on improving the effectiveness of their ESS process.

A decision was made to follow the Advanced Screening Technology Semi-nar recommendations made by Dr. G. Hobbs,[1] C.E. (Neil) Mandel, Jr.,[2] and R Mercado.[3] Advanced ESS involves continuous operational monitoring during exposure to ultra-high-rate thermal cycling with simultaneous stimulation of 6DoF broadband random vibration.

Cost, schedule, and capability bids were received from original equipment manufacturers (OEMs) A and B for advanced screening equipment that offered 6DoF random vibration conducted simultaneously with high-rate thermal cycling. Plans were initiated to install an advanced ESS chamber at Quanta Laboratories for initial use by Quanta for UDLP products.

In searching for equipment, the authors' key criterion for ESS was to assure that the *product output response* of all of a product's components results in a sensible degree of uniformly high stresses in the appropriate ESS vibration environment. This needs to be true for multiples of the product as well, and is a prerequisite to repetitively and reliably precipitate hidden (latent) flaws/defects in materials, processes, or design.

A word of caution: *Once a firm locks into ESS equipment and processes that are not effective cost-wise or technically, it is monumentally difficult to later justify the cost of making a change to higher-level management. A wrong decision may appear to have good immediate payback but may prove disastrous in the future.*

In the process of separating fact from promotion and advertisement the two leading systems—OEMs A and B—were evaluated extensively. To assure accurate gathering of test data, manufacturers of these systems were contacted to participate and witness these tests. One or more representatives from each company was present to guide operation of, and if necessary to make tuning adjustments to, their respective systems.

The areas of most interest to the authors were vibration level uniformity, auditory noise levels, temperature ramp rates, and temperature distribution. However, due to special ducting that existed in one of the systems available for us to test, it was not possible to make a meaningful compar-ison of temperature measurements. *Therefore, only vibration and noise measurement results are presented in this article.*

Vibration measurement

The efficacy of shock response spectrum (SRS) analysis for ESS vibration parameter response measurement has been proposed by some ESS experts as not only the best, but sometimes the only true measurement. The authors of this article question these propositions, and so do some others.[4,5] "Neither ASD [acceleration spec-tral density] nor SRS alone are a complete measure of screen/test strength. There is still 'a gap in the derivation' to link any vibration measurement to screen strength (for ESS) or product strength (HALT/STRIFE). The strength of a regimen is a consequence of its effectiveness—exposing the flaws or design marginalities."[6] [HALT™* = highly accelerated life testing; STRIFE™* = stress and life testing.]

Importance of uniformity

The need for repeatability—realistic uniformity of response to environmental stimulation—has been questioned by some ESS experts. Respected ESS instructors recommend that product output response is what must be met, not vibration table inputs or thermal chamber air flow temperature.

The authors believe that the need for reasonable repeatability and uniformity is imperative to developing a cost-effective ESS program. When there are large varia-tions in table response and great variations between X, Y, and Z axes, it appears impossible to assert that a screen is both effective and non-damaging. Furthermore, UDLP as a contractor is a design agent and a system integrator with total contractual responsibility for ESS. It is mandatory that UDLP identify clear, understandable ESS requirements to competing subcontractors and suppliers.

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***Key contributors** to this article include J. Birlew and N. Nishimura of UDLP, and T. Papadopoulos of Quanta.*

It is very difficult, if not impossible, to prepare an ESS manufacturing process procedure when using either of the 6DoF chambers that were evaluated, due to the inconsistencies and large variations in vibration levels. The dilemma facing UDLP is this: After developing ESS parameters, how does the hardware designer communicate this information to a manufacturer? Likewise, how can a reputable test laboratory offer signed and documented certification of the ESS stress parameters applied to his customer's product? This is especially critical if the product output response to environmental stimuli is either unknown or can have a variation of 2.7-to-one.

Tight ESS tolerances?

Some equipment manufacturers claim uniform, repeatable vibration tolerances are not needed. Assuming design ruggedization *(a robust design to begin with)* as a precursor to HALT, all units can be subjected to an ESS level high enough to precipitate flaws/defects, say these manufacturers. Papers have been developed supporting this reasoning, such as "*Is Uniformity and Repeatability Essential to Vibration and Temperature Screening?*"[7]

This paper claimed that the proof of screen (POS) is sufficient to verify that no serious damage has been imposed upon the product screened. The article has some strong points to consider. However, there are also weak points, which include:

- The referenced Santa Barbara ESS research work was done in 1980 on different equipment than that evaluated here;
- The four ESS articles referenced are all of older vintage, with dates from 1981 to 1982;
- Two of the five figures shown are classified by the writers as hypothetical;
- Temperature and vibration varia-tions throughout the chamber are identified to be "without concern for the variation if and only if a proper POS has been done."This implies a very robust design to begin with, which is not always an available luxury in either commercial or military electronics, whether in new or already manufac-tured products.

Although it may be true that neither strict uniformity nor repeatability is necessary, the definition of "strict" *should not mean without reasonable limits of uniformity.*

It is recognized that the tight test

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parameter tolerances usually specified for qualification specification tests are not necessary for ESS. Those parameters may be expanded significantly for ESS tolerances. Nevertheless, a screen is a process, and like all manufacturing processes, it must be controlled to be repetitively effective. Therefore, the authors agressively propose the need for practical uniformity of vibration response.

When evaluating the two ESS chambers discussed in this paper, it was assumed that ESS parameters developed for a product placed on the center of the table would be accurately reproduced in production with multiple units in a similar setup. However, results of our testing showed that table response in development could not be accurately reproduced for a production setup.

ESS equipment options

Some ESS instructors, who are also the OEMs of Systems A and B, claim that the best technical and cost-effective approach to ESS should be to use systems similar to theirs.

The authors had supported the equipment proposed by OEMs A and B without question for more than seven years. However, this support is now questioned by the authors and by others experienced in ESS technology. Hank Caruso says, "There are many valid options for applying environmental stress in different situations. Readers should be suspicious of 'technical' articles that try to restrict or discredit these options (especially if the author seems to have a commercial interest in the product being described). Insist that performance claims be verified in non-commercial language using valid physics. Understand your options. Reputable vendors can help provide this understanding. Remember, sales gimmicks are not physics, acronyms are not science, and a catalog is not a professional discipline."[8]

We authors now conclude that more work needs to be done (similar to Taguchi experiments) about making comparisons between 6DoF and alternate ESS processes and equipment, including vectored fixtures.

The OEMs' equipment justification has also been based upon experiential statements such as, "We have screened many thousands of parts this way, and precipitated numerous defects without damaging parts." Someone from one of the OEMs in this article wrote a paper on this. His supporting argument was, "Proof of screen following the production ESS process verifies that no significant damage has been imposed upon the parts."

This statement is partially true, but the conclusions appear to involve weak reasoning that is more circular than scientific. That is, in the argument or proof he uses a conclusion to be proved, or one of its unproved ***consequences***. POS does verify that no significant damage occurred to the product, but it *does not assure that an adequate, high-strength or a benign screen was used.*

It is difficult to accept a system on faith simply because it is said to have worked on thousands of parts that were claimed to be *very robust prior to ESS.* If a part is so robust that extremely high vibration levels can be imposed to accommodate the pattern of low to high levels, then the part is probably over-designed and will cost too much.

It is claimed by both OEMs that their tables have tuning features to adjust table and product response, although the results of this were not observed during our testing. Even if tuning can make the necessary adjustments for uniformity of vibration, it would still be a problem. Tuning the table for one product unit may be possible; however, tuning the table for multiple product units on a production basis is not. It would result in labor-intensive processes requiring skilled technicians to tune and re-tune as the products were changed.

It is claimed by one manufacturer that a "damped, modally rich segmented quasi-random shaker table"[9] may have a smoother profile (g2/Hz versus frequency), but the evaluation results documented in this article do not bear this out.

Additionally, because of its segmented design, this equipment seems to be limited in the maximum gRMS table input it can accept without causing damage to the segments. The lower gRMS is normally suitable for production runs, but it is unacceptable for the higher g needed for HALT during screening development. Based on experience, HALT is generally accepted as two times greater than the production vibration parameter (Figure 1).

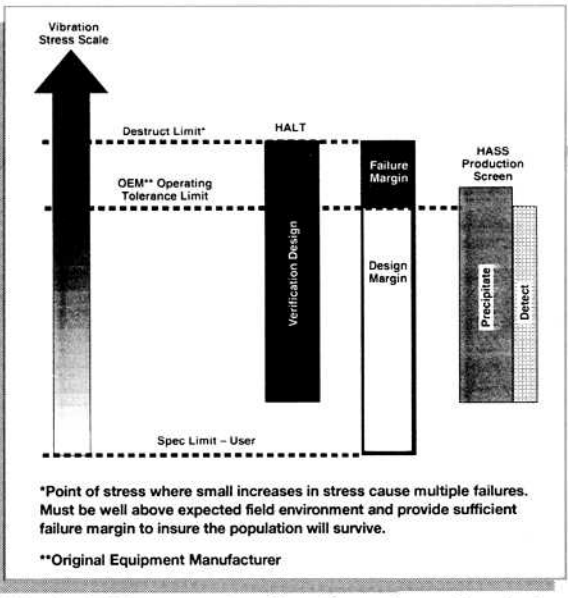
Equipment test and evaluation

During testing, nine triaxial accelerometers were used to measure uniformity of table response. The locations of the accelerometers are shown in Figure 2. It is important to recognize that the table input control accelerometers for each system are quite different:

- System A has two triaxial system accelerometers that control averaged table inputs;
- System B has one single-axis accelerometer mounted beneath the table, which measured gRMS in the table Z axis.

OEM B claims their system is 6DoF, yet only one single-axis table-control accelerometer is located under the table. It is scientifically difficult to understand how a single-axis control sensor can be considered as a suitable control for 6DoF equipment. Where is the control over the other five degrees of freedom?

Although not mandatory in testing, it is preferable to have more than one sensor. The second sensor can be used merely as a check, and not as a parameter-averaging sensor. If one sensor gets out of calibration, there should be a second for comparison to sound an alarm. This simple precaution may prevent many parts from being screened beyond process limits until the next calibration of the first sensor occurs.



*Point of stress where small increases in stress cause multiple failures. Must be well above expected field environment and provide sufficient failure margin to insure the population will survive.

**Original Equipment Manufacturer

FIG. 1—ESS separate vibration stress levels for robust designs.

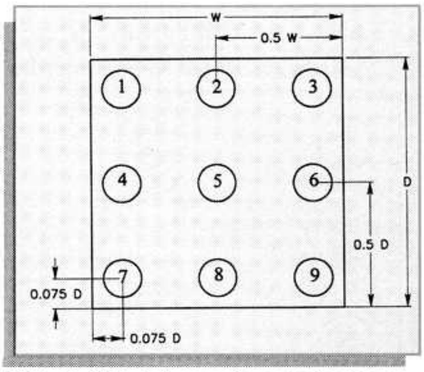


FIG. 2—Trixial accelerometer locations.

Key considerations

Some key considerations that affect choice of ESS equipment are:

- One purpose of ESS is to find defects in design and then to modify prototype units to become robust production units;
- Most commercial and some military parts are not inherently robust; therefore OEM A and B equipment may produce benign vibration screens on many parts on the same table;
- The authors see no scientific comparison that proves the vibration screen effectiveness or damage produced by the simulated 3DoF or 6DoF approaches discussed in this article;
- Until verifiable comparative test evidence is available that 6DoF is superior to simulated 3DoF, this should not be a key consideration in equipment selection;
- Data comparing effectiveness of coherent and non-coherent stimulation does not seem to be available. Until comparative test data on the superiority of non-coherency over coherency becomes available, this too should not be a key consideration in equipment selection.

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Vibration measurements

From actual test results, the following general observations were made for both systems:

1. Due to multiple sources of excitation of these systems, the vibration levels vary greatly from one location to another on the same table. gRMS levels at different places on the same vibration table differed as much as 2.7 times from one another (Tables 1–4);
2. The ratio of gRMS levels varies between different axes—X/Z;[1] Y/Z, and X/Y vary greatly from one point to another. The range of these ratios varies from 0.58 to as high as 2.54 for System B at an input level of 30 gRMS, i.e., Y is 58 percent of Z at one point, and Y is 254 percent of Z at another;
3. The high energy input spectra generated by these systems were found primarily at higher frequencies. Almost no energy was observed below 50 Hz (see Figures 3–6). Vibration energy at these low frequencies is often needed for effective environmental stress screening.

From the variations around both tables, and based on Miner's Fatigue Damage Accumulation Criteria, the fatigue damage imparted to one product unit would be more than 20,000 times greater than to another unit on the same table. Thus one product unit may have received a high-level ESS stress while another may have received a relatively benign stress.

Differences in characteristics

Some differences in characteristics were found between the two systems. The ones investigated are as follows:

1. System B can attain a much higher vibration level than can System A. The maximum computed vibration vector for System A was 55.9 gRMS; for System B it was 87.7 gRMS;
2. System B generates a smoother spectrum than System A in frequencies below 2000 Hz. Above 2000 Hz, the spectrum of System A is smoother than that of System B (see Figures 3–6). System A did not exhibit good repeatability at levels between 23.3 and 25.5 gRMS, as measured by linear averaging of triaxial table-input control accelerometers. These were the only gRMS levels evaluated; good repeatability at other levels remains to be seen.
3. Neither System A or B can cut out vibration energy input at higher frequencies. The spectrum of System A slopes off more rapidly than System B's at frequencies above 2000 Hz (see Figures 3–6). gRMS levels of System A, in the frequency range of 5–2000 Hz and that of 5–4000 Hz, were similar in magnitude (see Table 5). For System B, gRMS levels were significantly different in these same frequency ranges. When the frequency range of 5–2000 Hz was increased to 5–4000 Hz, gRMS levels more than doubled for the printed circuit board under test in System B.

System B was evaluated with a rubber type sheet across the table to minimize thermal heat transfer and to allegedly dampen out the high-frequency energy that could cause part damage. The printed circuit board holding fixture was screened with this dampening material,

TABLE 1—Vibration Survey (gRMS)
System A, 10 gRMS input, bare table

① X = 6.17 Y = 9.33 Z = 8.13	② X = 11.09 Y = 9.33 Z = 11.35	③ X = 8.32 Y = 5.50 Z = 8.91
X = 4.90 Y = 7.59 Z = 6.84 ⑧	X = 5.13 Y = 6.31 Z = 15.14 ⑨	X = 5.96 Y = 8.41 Z = 9.89 ④
X = 8.04 Y = 5.96 Z = 7.76 ⑦	X = 10.23 Y = 6.10 Z = 12.74 ⑥	X = 6.17 Y = 7.85 Z = 9.89 ⑤

TABLE 2—Vibration Survey (gRMS)
System A, Max g input, bare table

① X = 21.38 Y = 30.90 Z = 28.51	② X = 32.73 Y = 26.00 Z = 31.62	③ X = 27.23 Y = 20.18 Z = 32.73
X = 17.99 Y = 28.18 Z = 25.70 ⑧	X = 16.60 Y = 19.72 Z = 45.19 ⑨	X = 21.63 Y = 31.26 Z = 39.36 ④
X = 29.17 Y = 21.88 Z = 28.18 ⑦	X = 30.55 Y = 19.28 Z = 42.66 ⑥	X = 22.65 Y = 29.51 Z = 38.02 ⑤

TABLE 3—Vibration Survey (gRMS)
System B, 10 gRMS input, bare table

① X = 16.60 Y = 15.67 Z = 9.89	② X = 12.30 Y = 8.13 Z = 6.68	③ X = 16.79 Y = 13.80 Z = 13.80
X = 10.23 Y = 11.89 Z = 12.88 ⑧	X = 7.76 Y = 7.50 Z = 15.49 ⑨	X = 9.66 Y = 18.20 Z = 12.45 ④
X = 15.67 Y = 10.59 Z = 14.45 ⑦	X = 12.59 Y = 8.81 Z = 8.81 ⑥	X = 16.60 Y = 19.05 Z = 10.00 ⑤

TABLE 4—Vibration Survey (gRMS)
System B, 30 gRMS input, bare table

① X = 45.71 Y = 48.98 Z = 19.05	② X = 33.50 Y = 26.30 Z = 25.41	③ X = 56.89 Y = 43.15 Z = 38.90
X = 34.67 Y = 35.08 Z = 44.67 ⑧	X = 21.13 Y = 27.23 Z = 46.77 ⑨	X = 29.17 Y = 51.29 Z = 38.46 ④
X = 51.29 Y = 51.88 Z = 31.62 ⑦	X = 42.66 Y = 31.99 Z = 32.36 ⑥	X = 53.70 Y = 59.57 Z = 34.67 ⑤

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[1] Where X is the vibration gRMS value in the side-to-side direction; Y is the gRMS value in the front-to-back direction; and Z is the gRMS value in the vertical direction.

yet high-frequency energy was still encountered as shown in Figures 3–6. High-frequency energy of this type causes damage to the screened product and contributes little to effective screening. This was observed firsthand: when a printed circuit board was subjected to high gRMS vibration input in System B, many components popped off the board.

4. In System A, where a 15-pound printed circuit board fixture was mounted at the center of the table, vibration levels were much lower in three orthogonal directions at the fixture's base than those of the bare table. Under similar conditions in system B, the vibration level in the Z direction was likewise reduced, but those in the X and Y directions were increased.

5. For System A, the variation in gRMS magnitude between three orthogonal axes is greater at the input level of 10 gRMS than at an input level of 25.5 gRMS. Also, the spread in gRMS magnitude for each similar-direction axis at different locations on the table is greater at the 10 gRMS input level. Just the reverse is true for System B.

Acoustic measurements

To determine the noise level of these systems during operation, sound pressure levels were recorded at different locations. Both systems were found to have noise levels below 86.8 decibels—within OSHA criteria and acceptable for use without ear protection. Upon written request, detailed acoustic measurement data can be made available by the authors.

Skewed-fixture approach

The authors propose another approach to ESS. Figure 7 shows a simple skewed fixture. When mounted upon a commonly available single-axis electrodynamic shaker system, with special springs, this fixture can simulate six degrees of vibrational freedom. The authors belive this represents significant progress in developing an alternate approach to cost-efffective advanced-technology ESS, an approach that is both economical and reasonably effective.

Tests are continuing on the skewed-fixture design, with and without spring mounts, using printed circuit boards to determine product output. The authors plan to publish a second technical article after additional testing is complete.

M/RAD Corporation proposes a somewhat simpler approach,[10] which is offered as an alternate until after the 6DoF equipment undergoes design improvements. These improvements will address the limitations identified here, and until increased effectiveness of 6DoF is proven by systematic evaluation of comparison tests with other ESS processes.

The authors point out that to skew (vector) or tilt a fixture or product on a single-axis shaker is not the same as giving it a three-axis vibration input.[11] Vectoring a product tends to result in the three orthogonal axes of the product having constant phase angles and amplitude relationships in the axes in the 3DoF mode. Adding springs to the fixture may tend to more closely simulate 6DoF and address coherency to some extent. However, data comparing effectiveness of coherent and non-coherent stimulation does not seem to be available.

Skewed-fixture advantages

1. *Reduced cost of ESS.* Most testing organizations already have uniaxial shaker systems that can be adapted, so only a skewed fixture is needed to start the vibration ESS program;

2. *Vibration input ratios on three orthogonal axes can be selected independently.* As the magnitude ratios of the three translational accelerations are related to the skewed angles of the fixture, any desired magnitude ratios of three orthogonal vibration levels can be easily obtained. Special springs attached to the fixture can be used for simulating three rotational accelerations.

The magnitudes between these components are a function of the position of the unit under test's center of gravity, in relation to the locations of the springs, as well as the spring constants. Magnitudes of these rotational accelerations can also be selected independently, but not as easily. As the rotational accelerations are generally much lower in magnitude than translational accelerations, we conclude that precise control of these rotational acceleration magnitudes is of secondary importance;

3. *Vibration levels are very uniform in comparison to current commercially available ESS systems.* Since a conventional shaker system has only one source of excitation, vibration levels on the same

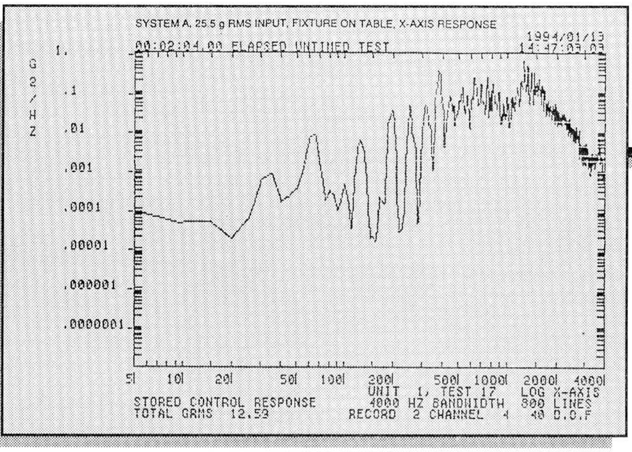

FIG. 3—System A spectral power density, X-axis.

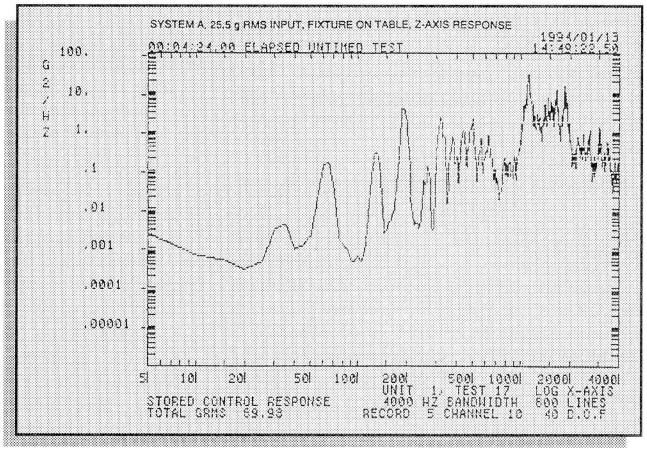

FIG. 4—System A spectral power density, Z-axis.

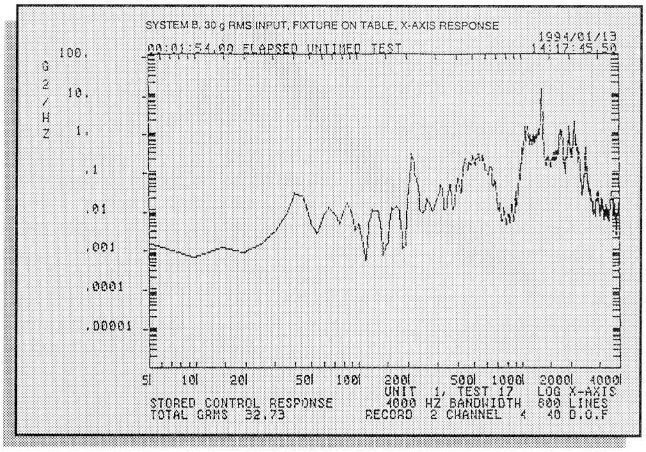

FIG. 5—System B spectral power density, X-axis.

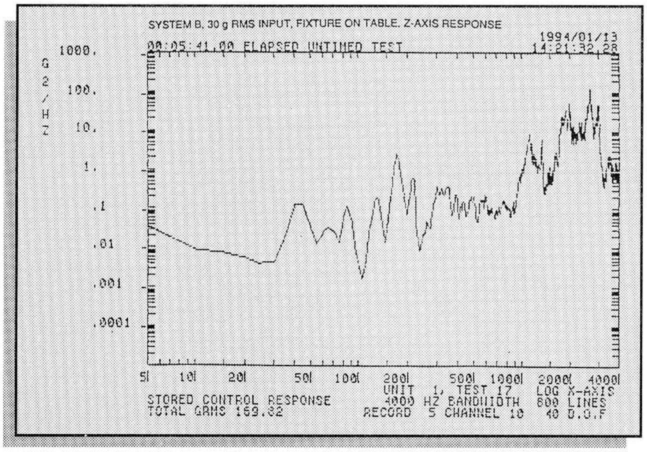

FIG. 6—System B spectral power density, Z-axis.

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table are uniform and can be controlled and shaped;

4. *Energy input vibration spectra can be shaped to almost any desired requirement.* Vibration control systems for conventional shakers are capable of generating virtually any spectrum. This helps eliminate the problem of very low energy at low frequencies and damaging high-frequency energies of the currently available pneumatic piston-excited ESS systems.

Testing of a prototype has shown that the skewed-fixture approach realizes many of the advantages identified above. The authors believe skewed fixtures can provide a low-cost, reasonably effective tool for ESS at least until a better ESS screening system is made available.

Skewed-fixture disadvantages

1. *Initial cost.* There is an initial, nonrecurring cost for the skewed fixture. Fixturing is much simpler with 6DoF systems;
2. *Limits quantity per run during vibration cycling.* Added size and weight of the skewed fixture is of little consequence in development ESS (HALT) in vibration. But it does tend to limit the quantity of items for each run in production ESS (HASS™*—highly accelerated stress screening). However, there is little to no effect upon quantities in production ESS during thermal cycling. This is because high-speed, ducted, directed airflow virtually eliminates the surrounding effects of high heat-capacity fixturing, tables, or chamber walls.

Conclusions

The authors conclude that while the two pieces of commercial equipment tested have some very good features, they need additional design improvement before either can be offered as a consistent, reliably effective tool for ESS. Remember, test results for A and B types of equipment did not produce reasonably predefined ratios between X/Z and Y/Z axes. They did produce very low energy at low frequencies and very high energy at high frequencies.

The bottom line is that the best process for ESS is the proven one—the one that reliably precipitates a significant majority of defects consistently, economically, and without reducing the product's operating life more than a small amount.

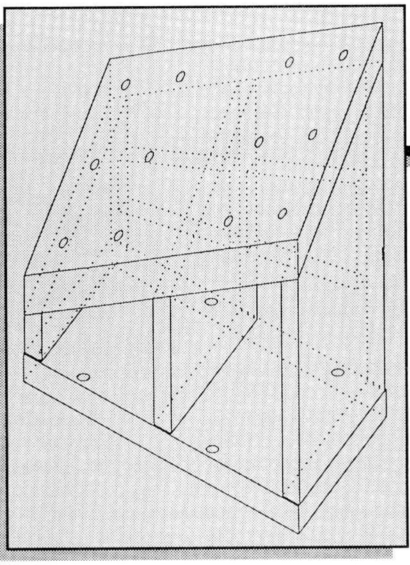

FIG. 7-A—Diagram of ESS skewed fixture; fixture is 5.5 in. x 10 in.; X = Y = 0.75Z.

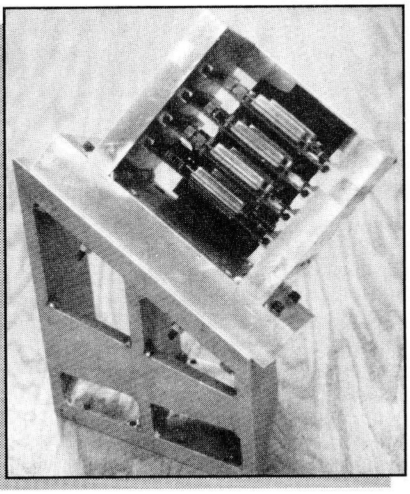

FIG. 7-B—Photo of actual ESS skewed fixture.

The authors propose their skewed-fixture design merely as a reliable but temporary alternate, until a better approach is developed. They recognize that their design has not been scientifically evaluated and proven to be the best approach to an ESS production process. However, they also question whether currently available 6DoF systems offer the best solution either.

If the cautions and concerns discussed in this article assist readers in the selection of suitable ESS processes and equipment for their particular needs, the authors' objectives have been met.

Professional courtesy extended

In June 1994, one of the principals of OEM B contacted one of the authors, advising that some table improvements have been made and evaluated on their 6DoF system. As a professional courtesy, we have excerpted quotes from the FAX as follows:

"We have taken data on our shakers with a new vibrator mounting concept and some of it is supplied below...As you can see, the balance is much better than it used to be. I have found that a variation by a factor of two is well within the bounds of acceptability for HALT and HASS applications.

"We have been making a steady series of changes to our systems to enhance performance in thermal cycling rates and uniformity, vibration uniformity and levels both high and low, sound levels as well as cosmetic and other refinements."

TABLE 5—VIBRATION LEVELS VS. FREQUENCY RANGES

SYSTEM A, MAX G INPUT, FIXTURE AT CENTER OF TABLE

FREQUENCY RANGE	FIXTURE BASE X-AXIS	FIXTURE BASE Y-AXIS	FIXTURE BASE Z-AXIS	CARD VERTICAL
5–2000 Hz	12.16 gRMS	10.00 gRMS	19.05 gRMS	66.07 gRMS
5–4000 Hz	12.59 gRMS	10.35 gRMS	19.50 gRMS	69.68 gRMS

SYSTEM B, 30 gRMS INPUT, FIXTURE AT CENTER OF TABLE

FREQUENCY RANGE	FIXTURE BASE X-AXIS	FIXTURE BASE Y-AXIS	FIXTURE BASE Z-AXIS	CARD VERTICAL
5–2000 Hz	29.51 gRMS	28.18 gRMS	21.38 gRMS	84.14 gRMS
5–4000 Hz	32.73 gRMS	35.48 gRMS	30.55 gRMS	169.82 gRMS

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