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THE HISTORY OF A DECISION: A STANDARD VIBRRATION TEST METHOD FOR QUALIFICATION

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Abstract

As Mil-Std-810G and subsequent versions have included multiple degree of freedom vibration test methodologies, it is important to understand the history and factors that drove the original decision in Mil-Std-810 to focus on single degree of freedom (SDOF) vibration testing. By assessing the factors and thought process of early Mil-Std-810 vibration test methods, it enables one to better consider the use of multiple degree of freedom testing now that it is feasible with today's technology and documented in Mil-Std-810. This papers delves into the details of the decision made in the 1960s for the SDOF vibration testing standards in Mil-Std-810 beyond the limitations of technology at the time. This paper also considers the implications for effective test planning today considering the advances in test capabilities and improvements in understanding of the operational environment.

Keywords: Six Degrees of Freedom, 6DOF, Vibration, Mil-Std-810, Single Degree of Freedom, SDOF

Introduction

1960: The United States (US) had survived World War II (WWII) and expanded on the tremendous growth in mechanical design experienced during the war. The war stimulated innovation – design of aircraft, ships, vehicles, equipment, sensors and weapons.

The US was also growing the fledgling capability made more important by the war efforts: performing qualification tests on equipment prior to use. The objective of qualification tests is to provide assurance that the equipment will perform as expected in the operational environment for which it is designed. One aspect of the operational environment is vibration and it proved troublesome. Several decades before 1960 had seen aircraft falling out of the sky, buildings acoustically unusable [1], weapons failing and equipment breaking [2] – all due to vibration.

Prior to 1940, environmental test, and in particular vibration testing, was practically non-existent. By the 1960s vibration test machines were advancing, as well as the understanding of the phenomena of vibration, the ability to

sense vibrations and the understanding of what it means. In fact, vibration testing for qualification was imperative because testing in the actual environment was costly, time consuming and in some cases, impossible [2].
However, vibration testing at one laboratory, such as Wright-Patterson Air Force Base (AFB) in Ohio, is different from that performed at other laboratories (labs). There are few standard procedures and many deficiencies in test equipment and facilities. WWII provided the great push that drove the military and industry to expand testing capabilities but left a gap: standardization [2,3]. In the mid-1940s, each branch of the military issued their own, and different, version of standards. There are as many as 10-12 different procedures for performing the same test [2]. There are many test labs, both government and industry, in existence and consistency and schools of thought are wide spread. The government and industry needed to establish a common approved methodology for qualification through vibration testing. A systems level approach to vibration test standardization was needed [4,5].
The decision made in 1960 and executed 1962-1967 with the release of MIL-STD-810, 810A and 810B, was a multi-method approach to vibration tests performed in a single direction (axis) at a time. This paper looks at the stakeholders, process and path that came to the decision which greatly affected the future of design and test in both the commercial and military industries [6].

Background

Vibration is important because rarely do machines fail due to excessive strain. Rather, they fail due to cracking because of excessive cyclical stress – fatigue. This failure mode is based on the number of cycles rather than tensile strength. Failures occur at stress levels far below the ultimate material strength [7].
Early vibration tests had to be performed in the real environment or with actual equipment in elaborate settings. In the late 1920's German scientists and engineers developed vibration machines and a way to use them to analyze elastic properties of structures to determine if they need to be made more rigid. These machines were mounted on a structure and used a series of rotating weights driven by a motor to create vibration. The US bought two and later refined the design in the late 1930s [8]. During WWII, the need for vibration tests grew and more machines and test labs were built. Testing on a vibration machine (shaker) became the preferred method to qualify vibration environments. By 1951 vibration tests were regularly used for qualification of components [9]. Tests, defined as SDOF tests, vibrate in a single axis at a time. Each of the three axes is tested independently. In the actual environment, vibrations occur in six degrees of freedom (6DOF) simultaneously. Analysis has demonstrated SDOF testing can result in over or under test [10]. One might wonder how the standardization of vibration testing started

with SDOF testing. The answer is not as simple as one might expect as there were multi-degree of freedom vibration test capabilities at the time of the initial release of Mil-Std-810. The answer has a long history.

Even after the first vibration machines and as late as the 1940's, tests were still performed with actual equipment or in the real environment. One example is where an engine, propeller and a section of a wing were tested in a wind tunnel because measurements couldn't be taken in flight and the vibration could not be replicated otherwise [11]. Another example is an engine modified so that is could run with some cylinders accessible to take vibration measurement on crankshafts [12]. These tests had to be performed because of the limitations of vibration test capabilities and were costly and complex. Stakeholders wanted to address these limitations. The Shock and Vibration Symposium (SVS) was started in 1947 to share ideas and tackle problems. Besides addressing problems caused by vibration, engineers were also using vibration to solve problems – mixing paints, sorting coal, and separating materials of different sizes. In 1956 the SVS lead, Elias Klein, points out the record number of attendees – all clamoring for specifications, environments and methods to test items [13]. In 1958, the Massachusetts Institute of Technology hosts summer sessions and papers to address the math, theory, analysis of vibration environments and testing [14]. It is in the middle of this fury of effort that the United States Air Force (USAF) tasks Virgil Junker with the important decision to develop a vibration test standard for all.

Decision Makers

In 1960, the US government was the major developer of new technologies (nuclear weapons and space program) which required qualification testing. While the concept of qualification testing would move to industry in the future, government programs were the main customers for the qualification process.

As such, the government was the most interested in the phenomena of vibration and sponsored the SVS. Since 1947, the SVS had met at least once a year as topics required. The meetings, and the papers published in the Shock and Vibration Bulletins, contained both classified and unclassified research in the area of shock and vibration. Not only government laboratories but the military, industry, academia, and test laboratories supported the symposium. Physicists, engineers, scientists, test engineers, program managers, end users, government officials and military leaders attended [13].

The US government was the key decision maker in the creation of a standard for vibration tests. Virgil Junker, Project Engineer of the USAF Environmental Criteria Branch was assigned responsibility for the decision. The Environmental Criteria Branch was under the Environmental Division, Directorate of Engineering Test, Deputy for

Test and Support of the USAF. While Junker was given ultimate responsibility to make the decision, he was encouraged to gain concurrence from the government, military and industry in the decision making process.

Objectives

The objective of the decision was to provide a common vibration test standard for qualification – one that could be used by all agencies, would result in repeatable laboratory tests and would save money by accelerating life and reducing test time while testing to real world conditions [15].

Limitations

Limitations on the decision were known prior to start of the effort. The vibration test standard was being created at the same time as standards for all environmental test methods (temperature, acceleration, sand, dust, shock, etc.). Junker was in charge of all of the decisions - a large body of work and multiple critical decisions. He had a common process for all the decisions, but each decision had its unique set of factors, biases and risks. With the broad scope of the effort, Junker realized some difference in opinion would always exist and some controversial points may never be resolved [5].

Additional limitations to the decision were the state of the technology at the time. These limitations became more apparent during the decision process. Though the scientists and engineers were discovering they could not measure the environment properly, test to the environment exactly nor interpret the test results exactly, they did not yet have the technology to correct the problems. The decision would be limited to what was feasible and practical at the time with suggestions for future improvement.

Alternatives

The vibration test standardization effort considered many alternatives. The alternatives were not all related and some were completely independent of each other. The solution required elements in each of three categories: the overall test objective, test method and test specification. Each solution alternative had a unique set of factors. These factors must be considered before a decision is made in any category. Alternatives considered for each category are described in Tables 1 through 3. Factors are described in tables 4 through 6.

Table 1: Alternatives - Test Objective Category
Simple, overly conservative tests - use deviations if the equipment fails and needs a lower test level [16]
Use existing specification such as Mil-E-5272and Mil-E-4970 and combine into a single specification [17, 18]
Understand damage potential – independent of an exact environment [19, 20]
Understand probability equipment will fail in service [21, 22]
Understand performance to exact environment [19,20]

Combined vibration and temperature tests - as a credible combination of tests [23]

Table 2: Alternatives - Test Method Category
Vibration testing via a circular motion on horizontal plane and circular motion in vertical plane [15]
Single axis vibration testing [20]
Multi-axis vibration testing - but no good way to test [20]
Vibration testing through torsional motion [15]
Use the state of the art in test technology and methods [22]
Update test standard but ensure test methods allow test labs to use existing equipment [15]

Table 3: Alternatives – Test Specification (or Level) Category
Continuous, Random vibration [24]
Discrete (sine sweeps) [17, 18]
Mixed discrete and random [25]
Durations and amplitude at worst case [22, 23, 24]
Duration and amplitudes adjusted for life of the particular application [22, 23, 24]
Test only the most damaging section of the environmental profile [24]
Make test standards rather than test specifications. Allow for tailorable specifications adjusted to application [22]

Factors and Biases

Technical factors were the reason a standard vibration test method was needed but they also made the decision very difficult. For well over a year, debate continued on the approach to the test levels and methods as well as the overall test objective or strategy. Some factors affected all the alternatives and some were specific to a certain alternative. Ultimately the decision was made based on technical premises rather than popular opinion and the factors were key to the decision. The factors reflect the difficulty of the decision.

Table 4: Test Objective Factors
Lab repeatability is main goal while correlation of service conditions with test realism must take a back seat [15]
Improper vibration tests or test levels cause the most expensive and largest number of rejects or reworks [22]
The test must be simple and feasible. Regardless of knowing the environment, smooth specifications (enveloped) are required because that is what the test equipment can do [16].
Test strategies should be common with other environmental test methods being prepared for the standard
Worst case method – old standards assumed if equipment can survive worst combination of worst conditions, then the equipment is good. But cannot afford this anymore nor take the hit to performance this causes – paying for vibration resistance that is not needed. [22]
Equipment must be designed/tested while service platform is not yet developed –environment not known yet [23]
Do not understand how damage is accrued in non-structural components (vacuum tubes, electronics, etc.) [24]
Can only measure the environment after the item is designed – too late to make changes in design. Need to understand environment and how equipment is damaged before a qualification test can be defined [24]

Table 4: Test Objective Factors
Instead of starting with complex environment, should start with simple, controlled, well understood lab tests. There is much not understood currently: cost or feasibility of full scale tests, duration of actual environment, lack of understanding of how to interpret data (from field and lab), lack of ability to measure data in the field, ability to understand data by controlling environment in lab, ability to determine cause of failures in test [26]
Need to reconcile differences between the existing standards while addressing new criteria for jet aircraft, missiles and space vehicles [2]
Lab test should support credible combinations of environments (i.e. temperature and vibration) [23]
Need to understand resonances as the vast majority of failures in the field (that can be duplicated in the lab) are associated with some sort of resonance phenomenon [23]
Need to understand the types of failures in the field – not just environment. Fatigue, wear, brinneling, loosening, malfunction, short or open circuit, contact chatter, brittle breakage [22, 23]

Table 5: Test Methods Factors
Vibration machines in WWII could only test up to 85 Hz even though it was known at the time engines caused vibrations up to 2,500 Hz. The old specifications reflected the capability of the vibration machines of the time [2]
Sandia Corporation has performed research on best methods to control and perform vibration tests and created a standard documenting the results [2, 27]
Very few labs have the capability to run combined vibration and temperature tests
When measuring an environment in the field, we don't take into account the interaction of the item on the platform so when we replicate on a vibration test machine we don't have a true translation. Thus we often over test as our smooth curve (enveloping) does not take into account the supporting structure's drop in impedance in resonant frequencies for the equipment [28, 29]
There is cross motion introduced and not controlled when performing a vibration test. This does not match cross motion seen in the field – even single axis machines have some cross motion [28, 29]
Vibration test machines were discovered to have substantial harmonics at higher frequencies in all 3 axes – even when shaking in 1 axis. The tables with gears and ball or roller bearings were significantly worse. Electrodynamic shakers are much better in this area. However, industry can't afford to get rid of all their old shakers – if they are only trying to test low frequency, they can use fixtures to dampen the high frequency effects. But if need to test high frequency, it is an issue [28]
Actual environments have significant higher frequency content than previously thought (above 55 Hz). Many existing vibration machines can't do higher frequencies or can't do random vibe (control system) [24]
Tests must consider the force on the test equipment and any resonances [16]
Test methods not totally understood. Lack of understanding of how to interpret data (from lab), lack of ability to understand data by controlling environment in lab, lack of ability to determine cause of failures in test [26]

Table 6: Test Specification Factors
Decision to make the test levels a specification or standard greatly impacts the levels chosen [30]
If the levels are a specification (requirement), equipment not be able to test to the given levels must make a deviation request to test in a different method or level [22]
Levels can be generic (very conservative) to cover all equipment regardless of location or multiple profiles can be given to support differences in environment based on location [2]
For functional (versus structural) equipment, need to determine if the equipment should be required to operate during vibration [2]

Table 6: Test Specification Factors
Equipment has resonance frequencies in approximately, but not the exact same frequency (unit to unit variability). If the environment is measured on 1 piece of equipment, the resulting specification cannot be exact as it may not be appropriate for next piece of equipment [22]
The sine sweeps in the old MIL-T and MIL-E documents didn't really reflect environment – it is actually just a test of transients. It is important to know how long to dwell at each frequency to prevent over or under test [25]
Afraid continuous vibration (random) would result in over-test. Not totally understood [24]
We are providing specifications for testing of components when we only have environment for the system [16]
Random vibration should be included. It is important for newer criteria such as missiles – data is available [2]
Should tests include higher frequency ranges when most labs don't have vibration machines to do this? And current measurements in field show vibrations at higher frequency with insignificant amplitudes? [2]
Standards or specifications group real measured data (i.e. all aircraft) but this does not let equipment take in account application – an enveloped spec for all aircraft is too high for equipment on light utility aircraft when compared to jets and bombers [2, 39]
Labs must accelerate time to failure with respect to service time. It is not feasible to test 20 years in the lab [23]

In addition to the technical factors, Junker indicated there were some biases among the stakeholders complicating the decision. These included:

- Bitter debates on test levels and how to do a test. Industry members claimed to be fed up as there was a great deal of money involved. They were tired of 'debates to devise tests to test tests to tests tests to determine whether a time function is truly statistical' and stated they 'could care less'. They just want to know what to design and test to [20].
- Legal and contractual challenges. While the main objective of a test specification is to qualify a system, secondary objectives can impose severe restrictions. Test specifications made part of legal contracts must be very clear and leave little to judgment and interpretation. This makes tailoring test levels hard [21].
- Misunderstandings of random vibration and Power Spectral Density (PSD) were rampant. People were asking if that means power applied to vibration machine. Better test methods were met with reluctance because they were not understood [24].
- Consistent passive resistance from military and industry to address combined environments (such as temperature and vibration) [2]

Decision Process

The issue was first defined among the stakeholders long before the decision effort was initiated. At the first SVS in 1947a future topic was requested to assess how closely current vibration tests simulate actual service conditions. By the mid-1950's vibration testing had advanced significantly but the stakeholders specifically stated much was needed to be understood about the strength of a test article and the nature of its environment before one could say a test procedure is adequate for qualification [24]. Debates included using random vibration to match an environment versus fatigue testing with the discrete sine sweep. In 1957, the horizontal test table (slip table) was invented and was such a huge breakthrough that it was predicted that most test labs would have one within 2 years. Electrical components were more common and were susceptible to higher vibration frequencies that structural components. 1956 saw the greatest number of attendees at the SVS as everyone was eager to find solutions [31].

The SVS was sponsored by the government and when the need was recognized for a decision on standard test methods, the government took on the responsibility to make the decision happen. The first step was a study, commissioned in 1960, to determine if a standard test method was a real need. The SVS was used as a tool to elicit stakeholder participation and buy in for the decision process.

The study was initiated to determine what measures could be taken to standardize vibration testing. The main criterion was to focus on existing specifications and create a single standard [17, 18, 32, 33].

Based on this direction, the process was to gather the information from the existing specifications, integrate into a single standard, and send out for review and release. As is common with many complex decisions, several iterations of the decision making process and alterations to the criteria occurred.

The decision process defined below and in Figure 1 is the final process that was implemented. Controversy with the various technical factors and the discovery that the old specifications were technically incorrect caused rework of the initial decision.

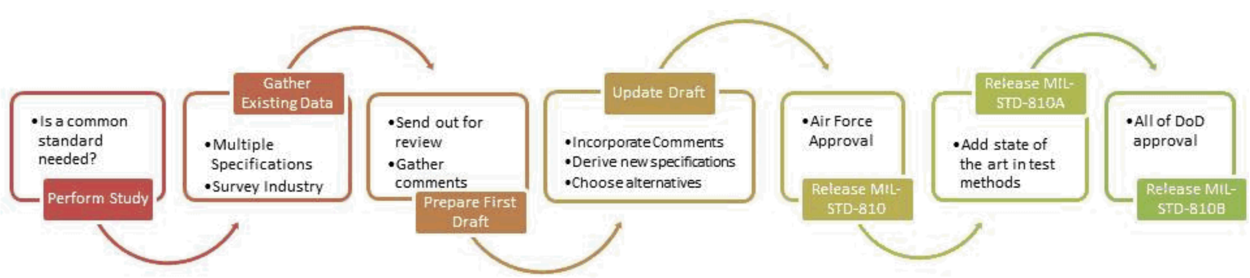

FIGURE 1 DECISION PROCESS – AS IMPLEMENTED

<u>Perform Study</u>: Junker had a team of engineers at Wright-Patterson AFB supporting the decision making process. The team helped to perform the study that was focused on stakeholder input from the SVS and interviews.

Gather Existing Data: The first step was to gather the old existing specifications from the various branches of the military. The second step was to gather all the information from papers and experts on fallacies of current methods and state of the art for new methods. A conscious decision (***new criteria***) was made not to include anything that a majority of existing labs could not perform or anything that research was still too new to prove the validity of the method.

Prepare First Draft: Two risks were immediately defined in preparing the first draft. First, consensus needed to be gained from an extremely large stakeholder base, which was difficult. Second, the methods in the old specifications contradicted each other so they could not be strictly combined. The first risk was mitigated by seeking Air Force approval only with the first release of the new standard (***new criteria***). The second risk was mitigated by using engineering judgment to choose the best test methods. It was also decided to make the document a standard and not a specification (requirement) (***new criteria***).

Update Draft: To mitigate the first risk, the draft was sent to 200 reviewers among the stakeholder base on Dec 20, 1961 and 111 responded [2]. This was better than predicted and reflected the interest in the topic. The comments were incorporated and a final version created.

Release MIL-STD-810: The first standard test method was released with Air Force approval. It was decided at this time, since the discovery of the fallacies of the old specifications, that the standard must be updated to reflect the state of the art and accurate specifications and a revision released. The document was revised with the input from industry through the SVS, panel discussions, votes and papers [20]. At this point, it was also decided to provide test levels that could be tailored and specified based on location in supporting platform (***new criteria***) [39]. A decision was also made to cancel the old conflicting specifications ***(new criteria***) [2].

Release MIL_STD_810A: The updated standard was released with Air Force approval. The document was then circulated and communicated with the other agencies (Army and Navy) for comments and update.

Release MIL_STD_810B: The updated standard is released by the Department of Defense with Air Force, Navy and Army approvals. A single standard decision had been achieved.

Timeline

Even though the topic of a standard vibration test method was discussed as early as 1947, the decision process did not actually start until 1960. Figure 2 shows the steps through the decision framework cycle with the dates [34]. Multiple iterations through the cycle were accomplished from 1960 – 1967.

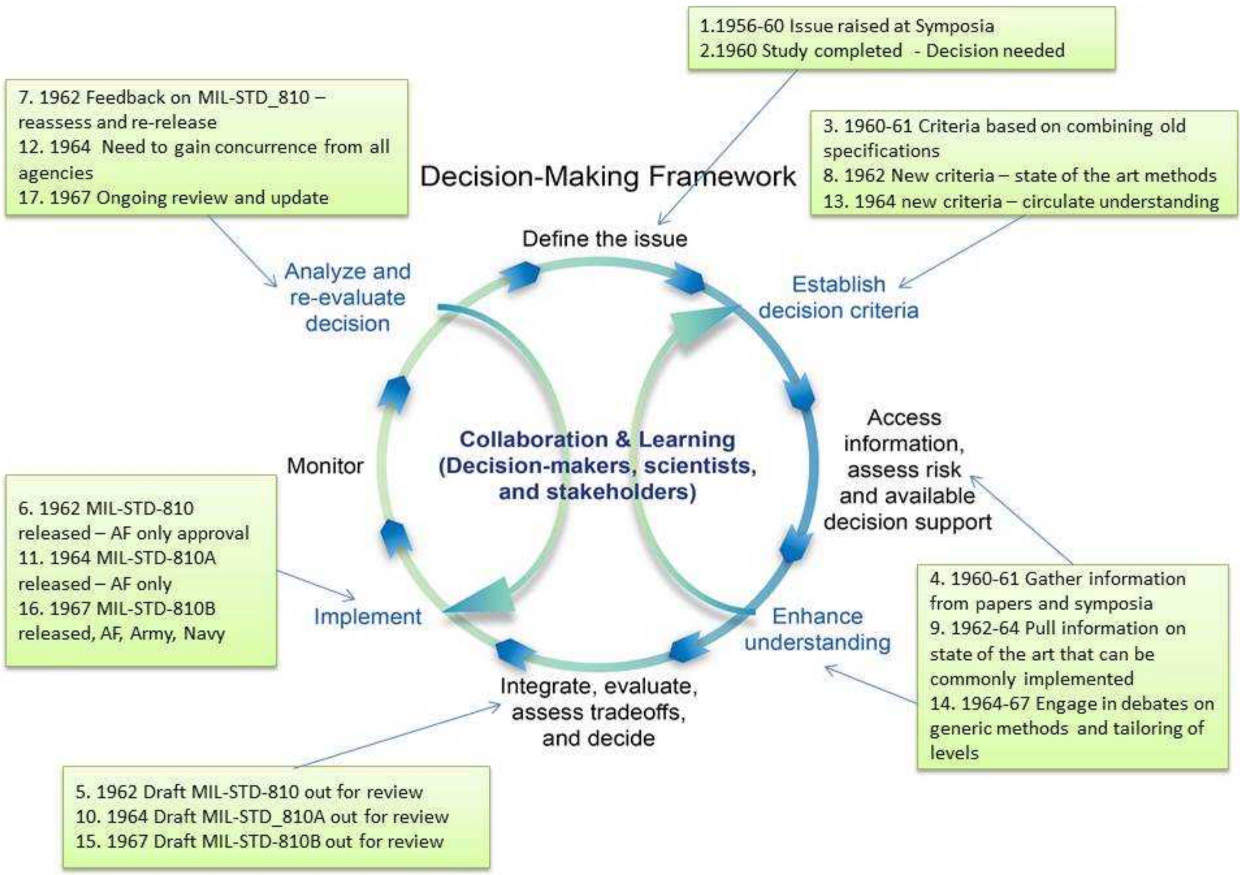

FIGURE 2: TIMELINE OF DECISION PROCESS ACTIVITIES

Decision Result

The cumulative result of the decision, documented in MIL-STD-810B, was a vibration test method standard that provided single axis tailorable vibration test methods in both discrete and random profiles based on equipment location and application defined at the most extreme expected levels. Highlighted sections in Table 7 reflect the results of the decision.

The **criteria** for the decision had been expanded to include:

- The test method will be a standard, not a specification.
- The test method will include state of the art but nothing on any newly performed research or anything to challenge the state of the art [2, 6].
- The test method will have concurrence of all three military agencies (Army, Navy, Air Force) [6, 35]
- The test method will have laboratory repeatability as the guiding criterion – correlation with service conditions and test realism had a lower priority [15].

- Tests levels will be based on the extreme conditions representing the minimum acceptable conditions for worldwide military use, but if one knows the environment is more or less severe, it can be tailored [2].
- Test levels will be based on application and location on service platform.
- It will be confusing to go to a new standard from old specifications. Must provide mapping of old specifications to new standard to support transition [2]
- The old specifications from various agencies will be cancelled.
- The test method will address guidance for combined environments (vibration and temperature)
- Since advances in space environments is limited, the standard will only offer limited guidance [2]
- The standard will be coordinated in phases – Air Force approval first, then wider audience will be sought

Table 7: Decision Result

Alternatives Highlighted in Yellow were Selected (table reflects MIL-STD-810A update)

Test Objective	Test Method	Test Specification (or Level)
Simple, overly conservative tests - use deviations if the equipment fails and needs a lower test level	Vibration testing via a circular motion on horizontal plane and circular motion in vertical plane	Continuous, Random vibration
Use existing specification such as Mil-E-5272and Mil-E-4970 and combine into a single specification	Single axis vibration testing	Discrete (sine sweeps)
Understand damage potential – independent of an exact environment	Multi-axis vibration testing - but no good way to test	Mixed discrete and random
Understand probability equipment will fail in service	Vibration testing through torsional motion	Durations and amplitude at worst case
Understand performance to exact environment	Use the state of the art in test technology and methods	Duration and amplitudes adjusted for life of the particular application
Combined vibration and temperature tests - as a credible combination of tests	Update test standard but do not change test methods such that current test laboratories cannot use existing equipment	Test only the most damaging section of the environmental profile
		Make a test standard rather than a test specification. Allow for tailorable specifications – adjust to application

Conclusion

The decision to establish a standard vibration test method used by all government agencies was executed. The SDOF based standard was driven by a decision to implement a standard that could be used by all laboratories and would generate repeatable results. This decision made sense at the time. However, the standard was not chosen to be a best replication of the environment. While it took some years to achieve the final goal, it did result in a coordinated decision that became the basis for work still vitally important today – 50 years later. Today, many tests are focusing on how to best replicate the environment. Now that 6DOF or Multiple Degree of Freedom (MDOF) testing is more available, the tradeoffs between SDOF and MDOF should be understood and considered for the appropriate test objectives, methods and specifications.

Epilogue

The first MIL-STD-810 was a 66-page document and has transformed into almost 1000 pages with the issue of Mil-Std-810G, Change 1 in 2014 [36]. The standard is recognized internationally as reliable guidance for environmental test. Have the vibration test methods for qualification, the result of this decision, stayed the same? Not surprisingly, they have not. With advances in technology affecting the test article, sensors, vibration machines and their controllers, the landscape is vastly different [30]. The ability to sense and measure the actual operational environment and the ability to perform random vibration tests successfully have driven the vibration test methods to replicate the operational environment rather than perform a repeatable ruggedness test. Even further advances in vibration machines and controllers have led to simulation of the environment in MDOF [37]. The standard focuses on tailoring the test specification for the actual system so that planning qualification, environments engineering and systems engineering occur early in the design process [36]. There is no longer a one size fits all specification because of the widely available technology [30].

Questions have been raised as MIL-STD-810 has been updated with the latest and greatest technology and methods: Has the original intent of the particular test method been reevaluated? Junker states there were very specific goals for each test method [2]. As test methods are updated, are they repurposed without reassessing the big picture? In some cases, this can result in a test that is not meaningful and perhaps not a true qualification test. One example questioned as Mil-Std-810 progressed is the minimum integrity vibration test [38]. One may ask how new technology is incorporated. An example is the multi-exciter test method added to MIL-STD-810. It describes MDOF testing yet can only offer single axis levels which could result in over or under test. The standard recommends development of MDOF test levels for the particular application [36]. This provides flexibility for labs with MDOF testing capabilities even though the capability is still being refined.

The ongoing problem in vibration testing: How can we learn what is true of the natural and induced environment in which the equipment must operate? How can we more closely simulate that environment? Do we hinder ourselves knowing so much of the environment because we lose sight of the big picture? Yet as well as we know the environment, we must still consider more severe levels because items may not perform as well in the hands of less capable users or under inadequate maintenance resulting from combat or other dire conditions [39]. It is the author's belief that, due to the complexity of factors, the standard vibration test method decision will be revisited many times in the future.

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