Highlights of the Next-Generation AIAA Moving Mechanical Assemblies Standard

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Abstract

Over the past several years, an effort has been under way to transform the previously released AIAA S-114 (2005) standard (Moving Mechanical Assemblies for Space and Launch Vehicles) into a more modern set of requirements to complement the way many space acquisition programs have evolved. A joint government/industry committee of mechanisms-minded subject matter experts was formed, and the previous standard was reviewed cover-to-cover by that committee for opportunities to make it reflect modern-day philosophies. The actual standard, tentatively designated AIAA S-114A, has not yet been released as of the publication of this paper, since it is currently making its way through final formatting and the approval process, but this paper discusses the most significant changes in a general way as a preview of what will be seen in the final release.

Introduction

15 years…that is a long time! Uber and Lyft did not exist to deliver us door-to-door yet. Instagram and Snapchat had not yet taken over our teenagers' lives. Even the ubiquitous iPad was still 5 years away! But that is how long it has been since the AIAA standard "Moving Mechanical Assemblies for Space and Launch Vehicles" was first released. New technologies and products, better methodologies, and smarter, more innovative ways of performing testing and analysis have all come along in that time, creating the need for a more up-to-date set of requirements to design, build, and test moving mechanical assemblies.

This paper includes a qualitative description of the update process and the more significant changes that resulted and will be found in the new Moving Mechanical Assemblies (MMA) standard, tentatively and likely designated as AIAA S-114A. After concurrence was received from AIAA to move forward with the update, the authors sent out invitations to government and industry stakeholders in the mechanisms expertise area to participate on a committee of such subject matter experts. That committee's charter was to approve by consensus the changes best suited for incorporation into the updated standard, such that it would be the best compromise of cost-effective requirements and guidelines to produce robust MMAs for space and launch vehicle applications.

Much of the MMA standard's material in the form of requirements has been retained since there was already significant sound work done by the previous committee that produced the 2005 version of the standard. However, that committee did run short on time to address some shortcomings, specifically in the testing section. As a result, the testing section was a top priority in this update effort. It has been reformatted and rewritten, with a goal of emulating the format of SMC-S-016 (also TR-RS-2014-00016, or formerly MIL-STD-1540C), "Test Requirements for Launch, Upper Stage, and Space Vehicles" (References 1, 2, and 3).

Moreover, a completely new approach to calculating force/torque margin is presented in this new revision. It specifies reduced margins over certain characteristic resistances that are more predictable or repeatable, but maintains the original margins for variable resistances such as friction. A detailed explanation of the process, and even a working example, are included in the new version of the standard.

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Perhaps the next most significant change that users of the new MMA standard will notice is the elimination of the “shall, where practical” weighting level of requirements. These requirements were deemed to be unverifiable and thus, difficult to enforce. A concerted parsing effort was launched to identify each of these approximately 90 instances in the standard, and to either upgrade each occurrence to a “shall” weighting level requirement, or downgrade it to a “should” weighting level for best practice or guidance. An additional goal of this parsing effort was to identify all of the requirements that were vaguely worded or non-verifiable. For example, approximately 40 additional requirements that used terms such as “shall be considered” or “shall be minimized” were found and corrected or modified.

Overall, more than 350 comments and requests for revisions were compiled by the government and industry committee working on this revision. Each comment was discussed and adjudicated by consensus. The comments fell within three broad categories: testing related, non-testing related, or parsing to eliminate all instances of the “shall, where practical” weighting level and other vague requirements. This paper will summarize the more significant changes that are expected to be published in AIAA S-114A.

The MMA Update Process and Industry Committee

Starting at a low-level of effort in 2014, the authors of this paper reviewed the material in the previous standard that had been repeatedly identified as credibly contentious, outdated, or troublesome, based on repeated mutual experience in program tailoring efforts, hardware testing campaigns, and day-to-day discussions and working-level meetings with customers and space and launch vehicle organizations. These items were categorized into three areas:

- The “shall, where practical” weighting factor
- The clarity, sequence/flow, and completeness of the testing section
- Other items identified as needing timely updates or maturation, based on real-life experience since the last standard’s release

All items of all categories were compiled into a comment resolution matrix (CRM) in a spreadsheet format (see Figure 1 for sample excerpt) in order to track what the original and proposed change to the text was, and the rationale for changing it.

Comment Author	Organization				Comments and Recommended Changes					
		Section	Subject	Comment Type	Existing Content /text	Proposed content/text	Rationale	Committee Discussion Comments	Committee Disposition	Verified as Implemented?
Boesiger	Lockheed Martin Space	8.1.2		Technical	at the vehicle test level	at the vehicle test level if accessible	cannot see them all at vehicle level		Accepted	Yes
Brandan Robertson	NASA	8.1.2.c	Typical inspection elements	Technical	fastener torque - torque on pre-selected fasteners before and after exposure to each environmental test condition	fastener torque - torque on pre-selected fasteners or a check of torque striping before and after exposure to each environmental test condition	Torque striping is a simple, inexpensive, and effective check on fastener loosening that is for some reason often overlooked.	Consider incorporating this into re-write as described in comment 29. (maybe add "where used") See proposed language in comment 89	Accepted with Changes	Yes
D. Shelton	Lockheed Martin Space	8.2	Test Instrumentation	Technical	Test instrumentation should be calibrated in place through the test electronics and in the environmental conditions of the test.	Delete	Test instrumentation may be fully calibrated or may be reference only for a development test. Calibration should be covered in general up front in the document.	Test instrumentation SHALL be calibrated consisent with the environmental conditions of the test.	Accepted with Changes	Yes
Mark Balzer	JPL	8.2	Torque checks	Technical		?		Duplicate of other comments (e.g. 30)	Rejected	Yes

Figure 1. Sample CRM entries

The authors proposed many of the initial changes in the text of the new draft MMA standard document, where little or no contention among stakeholders or users of the standard was expected. Some examples of these were typographical and grammatical errors, practices that were no longer supported or followed by the bulk of the industry, etc. Other, more significant, proposed changes were left open-ended in the CRM for future resolution and adjudication by an industry committee of mechanisms subject matter experts.

Invitations were sent out as a call for participation on the industry committee to meet on a regular basis and adjudicate all identified CRM items. These invitations were sent to a wide variety of spacecraft, payload, and launch vehicle contractors, as well as government and general interest participants, as requested by AIAA, who also requested representation from academia, but no such individuals could be identified as specifically concerned with the subject matter of this standard. Once invitations had been accepted by a quorum of the aforementioned categories, regular periodic teleconferences were set up to discuss the CRM items and help adjudicate each one. Based on a preponderance of participation on those teleconferences, the recognized MMA Committee on Standards included the following individuals and organizations:

- Brian Gore — The Aerospace Corporation (Co-Chair/Author)
- Leon Gurevich — The Aerospace Corporation (Co-Chair/Author)
- Mark Balzer — Jet Propulsion Laboratory
- Ed Boesiger — Lockheed Martin Corporation
- Ray McVey — Raytheon (retired)
- Mike Pollard — Lockheed Martin Corporation
- Brandan Robertson — NASA Johnson Space Center
- Adam Sexton — Ball Corporation
- Tim Woodard — The Aerospace Corporation

Invitations were tentatively accepted by individuals at Boeing, ULA, and Northrop Grumman, but their participation in the periodic teleconferences was limited.

From early 2018 through April 2019, on approximately 2-week intervals, the committee met and discussed each of the CRM items, as well as contributed their organizations' concerns and additional CRM items to the list as the effort progressed. By the conclusion of the adjudication effort there were 136 Parsing items, 93 Testing items, and 117 Non-Testing (or "other") items (346 total) that were dispositioned as either accepted or rejected in the new standard.

The Most Significant Changes

The three most significant changes in the updated MMA standard are the removal of the "shall, where practical" weighting factor, a newly revamped testing section, and a significantly modified method to calculate force/torque margin. These changes are described in greater detail in the following sections.

Elimination of "Shall, Where Practical"

During the pre-committee phase of the document review, the standard was examined for all instances of the "shall, where practical" weighting level requirement. These instances were added as line items on a CRM tab labeled Parsing. Because of numerous program tailoring exercises where feedback was received from organizations unsure about how to treat these – are they real/actual requirements to be traced in a database or not? – the authors attempted to address each one on its own merit and either upgrade it to a strict "shall" requirement, or reduce it to a "should" type of guideline for recommended engineering practice. Each of these items was then discussed during the industry committee telecons, and a consensus was reached for each one. Overall, there were approximately 85 items designated at the "shall, where practical" weighting level in the 2005 version of the standard. Of those, only about 13 were upgraded to the "shall" weighting level, about 26 were downgraded to the "should, preferred, may" weighting level, 32 were absorbed and modified into the new testing section requirements, and 14 were removed entirely for being out of scope, not applicable, or covered by other requirements.

One should note that a simple comparison count of the number of "shall" requirements in the old vs. new standards is not meaningful, largely because of the reformatting of the testing section, in which many requirements are repeated at the unit, subsystem, and/or vehicle level of assembly, which was not delineated in that fashion in the old version.

Testing Section

During the previous update to the standard in 2005, AIAA deadlines limited the MMA Committee on Standards focus on the testing section. As a result, much of the previously existing material was still held over from the boiler plate language found in the (even then) decades-old processes and philosophies. With the current standard update, the testing area was the first area of emphasis to modernize, making it more usable and valuable to the engineers who employ it.

A realization was made by the authors that many of the same programs that have this MMA standard levied as a set of requirements also have other testing standards levied at the same time, such as those listed in References 1-4. Since the authors (and a compendium of MMA standard users on government programs) were most familiar with References 1 and 2, many of the same outline, structure, and philosophical elements found in those testing standards were duplicated in the new MMA standard where it made logical sense.

For example, the previous version of the MMA standard did not give any guidance or direction regarding which tests were intended to be performed at each level of assembly. To remedy this, the new MMA testing section mimics that of Reference 2, with separate Unit Level, Subsystem Level, and Vehicle Level test subsections. It was noted that one of the more referenced features in the testing standards is a table or matrix that indicates what testing should be done at which level. In order to assist the user even further in this area, a similar table was constructed for the MMA standard, and is shown in Figure 2.

With this table, one can see at a glance the required tests (and those requiring a formal evaluation to be conducted to determine if they are required) for each level of assembly, as well as for the test type (qualification, proto-qualification, or acceptance). Users of the standard will also notice that the slate of typical MMA tests have been broken down into broad categories such as Performance tests, Environmental Exposure tests, and “Special” tests.

Another omission in previous versions of MMA standards is any guidance regarding the flow of a testing program, and in what order these required tests should be performed. Many programmatic, personnel, or resource limitations can dictate the order of some testing flows, but there was no default or recommended order. As such, recommended test flows were added to the standard, with an example shown in Figure 3 that illustrates a typical test flow sequence one might employ for an MMA at the Unit Level. Additional, similar test sequences are provided in the standard for Subsystem and Vehicle Levels of assembly as well.

These sequences provide not only a default recommended order by which to conduct a test program, but also provide respective reference paragraphs in the document for more detail on each particular test. The reference paragraphs attempt to provide test-specific requirements as well as background information, such as the purpose of the test or other nuances that may help perform or set up a particular test. A simple color-coding scheme also identifies which tests may only be applicable for qualification or acceptance programs specifically.

	Reference Paragraph	Unit		Subsystem		Vehicle	
		Proto /Qual	Acceptance	Proto /Qual	Acceptance	Proto /Qual	Acceptance
Inspections							
Initial	8.1	R	R	R	R	R	R
Final	8.1	R	R	R	R	R	R
Performance Tests							
Release/First Motion(6)	8.5.3.3, 8.6.3.3, 8.7.3.3	R (1)	(2)	R	R	R	R
Deployment/Actuation	8.5.3.4, 8.6.3.4, 8.7.3.4	R	R	R	R	ER	ER
Force/Torque Margin	8.5.3.5, 8.6.3.5, 8.7.3.5	R	R	ER	ER	ER	ER
Pointing/Position Accuracy	8.5.3.6, 8.6.3.6, 8.7.3.6	R	R	R	R	R	R
Electrical	8.5.3.7, 8.6.3.7, 8.7.3.7	R	R	R	R	R	R
Environmental Exposure Tests	8.5.4, 8.6.4, 8.7.4	(3)	(3)	(3)	(3)	(3)	(3)
Special Tests							
Run-in	8.5.5.2	R	R	--	--	--	--
Proof Load	8.5.5.3	--	R(4)	--	--	--	--
Static Load	8.5.5.4, 8.6.5.3	R	--	R	--	--	--
Stiffness	8.5.5.5, 8.6.5.4	R	R	ER	ER	--	--
Release Margin (5)	8.5.5.6	R	--	--	--	--	--
Life	8.5.5.7	R(6)	--	--	--	--	--
Clearance	8.6.5.2, 8.7.5.2	--	--	R(7)	R	R(7)	R

Notes

R	Required
ER	Evaluation Required (See 8.3)
"--"	Not generally needed
(1)	Required for all release devices. For pyrotechnic devices, see Reference 2 for qualification req'ts.
(2)	See 8.5.3.3 for requirements for various device types
(3)	See Reference 1 for requirements for environmental exposure tests at each level of assembly
(4)	Applicable for workmanship-dependent items such as cables, swaged ends, composites, and adhesives.
(5)	Unit level: device (e.g., sepnut); Subsystem level: clampband (incl device); Vehicle level: may be same
	as subsystem unless hardware added
(6)	Applicable only for qualification, not protoqual
(7)	Applicable only for protoqualification hardware

Figure 2. Testing requirements matrix in new MMA standard

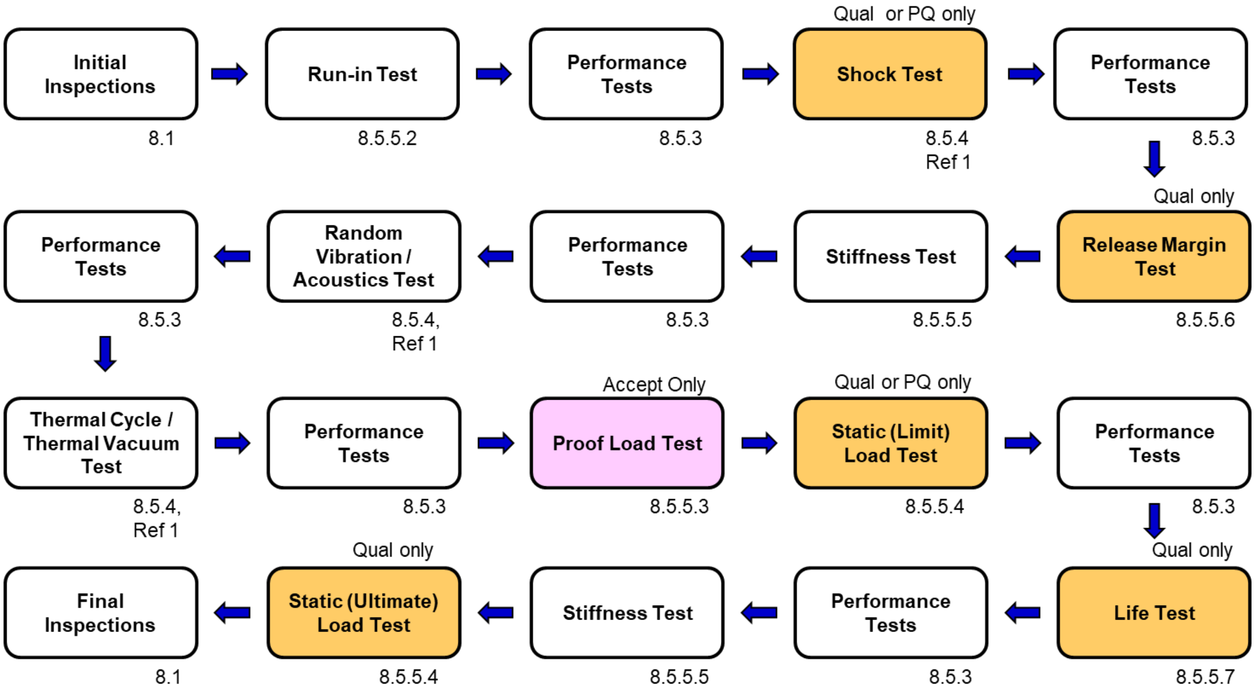

Figure 3: Typical MMA test sequence at unit level

<u>Torque/Force Margin Approach</u>

In this discussion, references to "torque margin" also apply to linear motion, with "force" simply replacing "torque."

This subject may be the biggest change in the new MMA standard, and one that will likely take the most adjustment with respect to the traditional approach for experienced MMA engineers. This new approach to calculating torque margin was first widely discussed around the time of the previous AIAA MMA standard release, but the aforementioned AIAA deadline prevented any further committee discussions on the matter. Furthermore, this approach has already been published in its basic form in NASA's MMA standard, Reference 5, but there were some modifications and accommodations made in this AIAA MMA Standard update.

The basic premise was that there are at least three different types of resistive forces that MMAs encounter – those that are relatively predictable and repeatable, those that are variable and harder to predict initially or over life, and those that are purely the result of an induced acceleration. Examples of the first kind, or "fixed" resistances, are a return or fail-safe spring, fluid pressure in a valve, etc. Examples of the second kind, or "variable" resistances, are coulomb friction, cable harness bending stiffness, etc. Examples of the third kind, or "acceleration-dependent" resistances, are those produced by rotary motion, launch vehicle acceleration, etc.

In the new torque margin calculation approach, which resembles the method in which stress or mass margins are calculated, each resistive torque carries with it a different uncertainty factor. Traditionally, with a torque margin requirement of 100%, all resistive torques were assigned an uncertainty factor of 2.0. In the new approach, the uncertainty factor is a function of the "variable" or "fixed" nature as described above, as well as of the method by which its value is obtained, such as by analysis, testing on an engineering model or qualification article, or testing on an actual flight unit. Figure 4 shows the minimum torque/force margin factors used in this new approach.

Source of Torque/Force Data	K_{fix}	K_{var}	K_{acc}
Theory or analysis	1.50	3.00	1.25
Test of engineering model, development, qualification, or lot acceptance hardware at respective environmental conditions; or flight hardware at ambient conditions	1.35	2.50	1.15
Test of flight hardware at acceptance environmental conditions	1.25	2.00	1.10
Value for one-spring-failed case	1.00	1.00	1.00

Figure 4: Minimum Torque/Force Margin Factors

Before discussing the new calculation method and equation(s), it is also worthwhile to mention that there are now five different types of torque/force margins identified, with the requirements of each needing to be satisfied as appropriate for a given MMA or subsystem:

- Static Torque/Force Margin – a measure of the excess torque available to overcome resistance to impending motion
- Constant Velocity Torque/Force Margin – a measure of the excess torque available to maintain motion
- Holding Torque/Force Margin – a measure of the excess torque available to maintain position in the presence of external disturbances
- Dynamic Torque/Force Margin – a measure of the excess torque available to accelerate a body by a given amount
- Stepper Motor Margin – a measure of the excess pull-in torque at the drive rate available to overcome friction loads seen at the motor

The new <u>single</u> equation used to calculate the torque/force margin is shown in Equation 1:

$$\text{Torque Margin} = \frac{T_{avail}}{\Sigma K_{fix} T_{fix} + \Sigma K_{var} T_{var} + \Sigma K_{acc} T_{acc}} - 1 \qquad (1)$$

where

- T_{avail} is the minimum available torque generated by the driving or holding component (e.g., spring, motor).
- T_{fix} terms are the individual maximum “fixed” resisting torques that are not strongly influenced by effects of friction, temperature, cycles, etc. (e.g., motor detent torque, vehicle maneuver-induced torque, return spring torque, unbalanced pressure load limited by relief mechanisms).
- T_{var} terms are the individual maximum “variable” resisting torques whose values may change with environmental conditions and cycles (e.g., friction torque, wire harness torque due to flexing or long term set).
- T_{acc} is the torque required to achieve the specified acceleration of the driven component.
- K_{fix}, K_{var}, and K_{acc} are the fixed, variable, and acceleration torque/force margin factors applied to each individual resisting torque/force term in Equation 1 prior to summation.

As mentioned earlier, torque/force margins are now calculated in the same manner as stress, strength, and mass margins. As such, the requirement for static torque margin is no longer 100%, but that it be <u>positive (> 0)</u>, after the appropriate uncertainty factors are applied. All terms in Equation 1 may not be used in all MMA applications, and further guidance for each type of margin is provided in the standard.

For stepper motor torque margin, engineers are given a choice to use either a step stability analysis or a pull-in torque margin analysis. The step stability analysis is stated as preferred, but the pull-in torque method is also acceptable, only when certain conditions are met. Equation 2 shows the pull-in torque margin calculation method.

$$\text{Pull-in torque margin} = \left\{\left(\frac{\text{Pull−in torque at drive rate}}{\text{Kvar} * \text{Total friction load seen by motor}}\right) - 1\right\} \quad (2)$$

When choosing the step stability analysis method instead, Equation 2 can be re-written to take the form of Equation 3

$$\text{Pull-in torque at drive rate} = [1 + \text{Pull-in Torque Margin}] * [\text{Total friction load seen by motor}] \quad (3)$$

Step stability is achieved when the left side of Equation 3 is greater than the right side. In the step stability analysis, the value of the [1+ Pull-in Torque Margin] term is increased until the motor goes unstable. The value from the last stable case is then used to calculate the stepper motor margin.

Summary and Path Forward

A multi-year effort has culminated with a finished draft of a newly updated AIAA Moving Mechanical Assemblies standard. The most significant changes have been discussed herein. These include the elimination of the “shall, where practical” requirement weighting level, a completely new testing section that mirrors other industry testing standards, and a more realistic approach to calculating torque/force margins. There are a host of other changes which were not highlighted in this paper, but which the authors and industry committee members believe will make a more robust and meaningful set of MMA requirements for space and launch vehicle programs in the future.

As of the submission of this paper (January 2020), the draft document is making its way through at least two approval processes, one by The Aerospace Corporation to replace the Mission Assurance Baseline callout of the previous MMA standard, and the other by the AIAA. It is anticipated that these will be completed sometime in 2020.

References

1. SMC-S-016, Air Force Space Command, Space and Missile Systems Center Standard, “Test Requirements for Launch, Upper Stage, and Space Vehicles,” September 2014.
2. TR-RS-2014-00016, The Aerospace Corporation, Technical Report, “Test Requirements for Launch, Upper-Stage, and Space Vehicles,” June 2014.
3. MIL-STD-1540C, Department of Defense, Military Standard, “Test Requirements for Launch, Upper-Stage, and Space Vehicles,” September 1994.
4. GSFC-STD-7000, NASA Technical Standard, “General Environmental Verification Standard (GEVS),” April 2013.
5. NASA-STD-5017A, NASA Technical Standard, “Design and Development Requirements for Mechanisms,” July 2015.

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