NASA Handbook 7005: Dynamics Environmental Criteria

Ali R. Kolaini
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

ABSTRACT

Since the NASA-HDBK-7005 first released in 2001, oversights and imprecise language leading to misinterpretations have been identified in the handbook and new issues in the discipline have arisen that need to be addressed. The majority of the technology described in handbook is mature and is standard practice among experts in the discipline. Advances in the discipline have been made in several areas and clarifications are needed in some of existing material. Many of these advances and clarifications are a product of new NASA launch vehicle program. The revision of the 7005 handbook benefits current NASA manned space flight program, NASA's numerous unmanned space missions, and the community at large. A community wide contribution is made and numerous suggestions have been offered for the revision. This paper summarizes sections of the handbook that have gone through significant revisions.

KEY WORDS: Spacecraft, Vibration, Testing, Sinusoidal, Random, Dynamics Environments Requirements, Fatigue

INTRODUCTION

The first version of the 7005 handbook was released in 2001 and provides detail information for the following:

a) The dynamic environments that a spacecraft might be exposed to during its service life from the completion of its manufacture to the completion of its mission.
b) The state-of-the-art procedures for predicting the dynamic excitations (loads) produced by the dynamic environments.
c) The state-of-the-art procedures for predicting the structural responses to the dynamic excitations.
d) The state of the art procedures for establishing dynamic criteria with appropriate margins for the design and testing of a spacecraft and its components.
e) The equipment and procedures used to test a spacecraft and its components.

Although written primarily for spacecraft, many sections of the handbook are useful for launch vehicle, aircraft, and ground transportation vehicle applications. The handbook covers a broad range of topics within the fields of aerospace structural dynamics and aeroacoustics. However, the guidelines provided in the handbook do not encompass all the engineering and management details necessary to successfully implement a spacecraft dynamics loads design and verification program.

Since the 231 page NASA-HDBK-7005 released in 2001, oversights and imprecise language leading to misinterpretations have been identified in the handbook and new issues in the discipline have arisen that need to be addressed. The bulk of the technology described in NASA-HDBK-

7005 is very mature and is standard practice among experts in the discipline. Much of the revision to the handbook will be making the text less subject to misinterpretation. Some technologies have advanced significantly in the last 15 years since the handbook was in development. For instance, numerical vibroacoustic analysis tools have greatly improved. Section 4 discusses direct measurements of external aerodynamic noise excitations and not quite correctly states that the microphones must be flush mounted to the outside surface of the vehicle. In 2004 an extensive series of scale model wind tunnel tests were performed as part of the Shuttle Return to Flight program. The microphone diaphragms were flush mounted, but the 2 mm protective caps were left on. This protuberance created a local flow disturbance and measured fluctuating pressure levels were several dBs higher than for identical conditions in the original Shuttle scale model wind tunnel tests conducted in 1975. After much consternation, the test results were discarded and the tests were correctly rerun in 2006. Section 4 also discusses direct measurements of external acoustic noise excitations and cite that the same microphones can be used for external aerodynamic noise measurements, but does not state that the protective caps can be left on for the acoustic tests, but must be removed for the aerodynamic tests.

The handbook contains only cursory descriptions of the statistical nature of random acoustic and vibration data. In particular, extreme peaks in the data are barely mentioned. It has become standard practice in most aerospace organizations to design structural elements for random vibration and acoustic loads to three sigma (i.e., 3 times the RMS acceleration, force, stress, displacement, etc.) However, laboratory vibration and acoustic test data shows that peaks will reach 5 sigma and higher in a one minute flight or test. This is of particular concern for the newer stiff, brittle structures which are much more susceptible to first passage exceedances than to fatigue damage. JPL has recently changed it's design practices for composites, mirrors, and other brittle materials to account for extreme peaks[1,2]. The NESC Loads and Dynamics Discipline specialist recently brought this issue to the attention of the NASA Chief Engineer. Section 8 on Design and Test Criteria needs to be rewritten to address extreme peaks and Probabilistic Damage Assessment methods need to be described in this section. Limiting criteria for extreme peaks need to be addressed in section 10 of the handbook.

There are standards that address the specification of dynamics environments such as NASA-STD-7001 “and MIL-STD-1540[3,4]. These standards specify test requirements, but do not provide “how to” information contained in NASA-HDBK-7005. The handbook documents the many advances in dynamics environments technology since the “watershed” period of aerospace research and development that occurred during the decade of the 1960s, often referred to as the Apollo era. Toward the end of this era, efforts were made to document and summarize the Apollo era developments, but NASA-HDBK-7005 is the only source that comprehensively summarizes, evaluates, and provides extensive references for the current state of the art developments in the discipline.

The need for updating the handbook has been particularly apparent in discussions within the community on formulating the new launch vehicles dynamics environments program. NASA-HDBK-7005 has been cited as the reference source for program development in a number of meetings and telecons and has been misinterpreted several times by managers and even discipline practitioners. A significant revision of the handbook is underway to include new methods and approaches that have been developed within the last 15 years.

Industry Wide Contributors

To revise the handbook industry wide involvement was sought and contributors from many organizations have extended their help to update the handbook on a voluntary basis. Table l lists names of the contributors organized based on disciplines. The contributors are divided into several topics: Low frequency vibration and loads led by Sam Yunis from LaRC, high-frequency dynamics led by Ali Kolaini of JPL, pyroshock led by Ali Kolaini, fatigue and extreme peaks led by Shahram Sarkani of University of Washington. Janice Houston, Robin Ferebee, and Darren Reed of SLS program provided information pertaining to the recent development and testing, Paul Blelloch and Ralph Brillhart of ATA Engineering and Bryce Gardener of ESA engineering provided updates on vibroacoustic prediction tools and modal testing, Tom Irvine provided updates on shock, Tim Widrick of KSC provided updates on statistical derivation of the random data, and many others listed in Table 1 contributed to the handbook revision.

Table 1: List of NASA and Industry Contributors

Loads, Low-Freq	Eli Rayos (JSC)
	Chia-Yen Peng (JPL)
	Paul Repacz (JPL)
	Ayman Abdallah (KSC)
	Tim Widrick (KSC)
	Jim Zimmerman (KSC)
	Sam Yunis (LaRC), Lead
	Dave McGhee (MSFC)
	Alvar Kabe (Aerospace)
	Paul Blelloch (ATA)
	Tom Howsman (DCI)
	Chris Flannigan (Quartus)
	Curt Larsen (NESC)
	Joel Sills (NESC)
	Vince Fogt (JSC)
	David Hall (ULA)
	Francis Gulick (ULA)
	Douglas Knox (SpaceX)
	Ralph Brillhart (ATA)
	Stephen Morgan (Boeing)
	Kenneth Schultz (NASA)
Fatique, Extreme peak, MPE	Paul Bremner (Quartus), Shahram Sarkani (GWU), Paul Blelock (ATA), Curt Larsen (NESC), Ali R. Kolaini
High Frequency	Bryan Song (KS)
	Jim Kinney (KSC)
	Paul Blellock (ATA)
	Robin Ferebee (MFSC)
	Andrew Smith (MFSC)
	Down Philips (MFSC)
	Bob Wingate (MFSC)
	Janet Houston (MFSC)
	Dave McGhee (MSFC)
	Bryce Gardner (ESI)
	Paul Bremner (Quartus)
	Joel Sills (NESC)
	Vince Fogt (JSC)
	Loern Yoshinaga (ULA)
	Bjorn Forssen (ULA)
	Ali R. Kolaini (Lead)
Shock	Robin Ferebee (MSFC)
	Dexter Johnson, Bill Hughes (GRC)
	Joel Sills, Vince Fogt (JSC)
	Tom Irvine (NESC)
	David Parsons (JPL)
	Daniel Kaufman (GFSC)
	Ali R. Kolaini (Lead)
Shaker, DFAT, RAFT	Michael Hale (Trideum Corp)
	Dexter Johnson (GRC)
	Joel Sills (NESC), Vince Fogt (JSC)
	Ali R. Kolaini
Testing	All
Transportation	Aymen Abdallah (KSC)
	Jim Kinney (KSC)
	Robin Ferebee (MSFC)
	Curt Larsen (NESC)
	Ali R. Kolaini
EDL, Payload Re-entery	Chia-Yen Peng (JPL), LaRC (?)

Modifications to Existing Handbook

The following summaries changes made to sections in the handbook:

- Section 1: Updated a few significant breakthroughs in modeling and testing technologies.

- Section 2: Added a few more references, and a new sub-section on pseudo velocity prediction.
- Section 3: The following new sub-sections are added or significant modification are made to the exciting sub-sections:
    - Space vehicle liquid rocket engine green run (new): Discusses the external acoustic environments generation during the launch vehicle model test.
    - Flight readiness firing (new): The acoustic environment from FRF must be accounted and designed for.
    - Igniter shock environment occurring prior to the ignition overpressure that begins after booster ignition, engine/motor overpressure, engine/motor generated acoustic loads, solid rocket motor pressure oscillations are discussed,
    - Multibody, impact and separation (new): There are many multibody problems in spacecraft/launch vehicle and launch vehicle design. These include liftoff from the pad, stage separation, and spacecraft/launch vehicle separation, parachute flight, docking, and landing. These events are all characterized by the fact that the forces between the bodies is unknown prior to simulation. Updated methods of analysis with references are provided in this sub-section.
    - Updated references.
- Section 4: The following new sub-sections are added or significant modification are made to the exciting sub-sections:
    - Launch vehicle liftoff excitations.
    - Spatial correlation.
    - Water injection.
    - Direct acoustic measurements.
    - New section on aeroacoustics predictions that includes new vibro-acoustic modeling methods such as Goody, Efimstov, and Rackl and Weston. These methods are briefly discussed. In addition to these methods the application of the aeroacoustics predictions to Martian atmosphere are also included.
    - Some of the discussion related to Statistical Energy Analysis (SEA) are moved to Appendix.
    - References are updated.
- Section 5: The following new sub-sections are added or significant modification are made to the exciting sub-sections:
    - Low-frequency vibration and transient analysis.
    - Norton Thevenin Receptance Coupling method (new): A new process that uses a coupled loads analysis method called Norton Thevenin Receptance Coupling (NTRC) is proposed. NTRC is a linear frequency domain coupled load analysis method that uses FFT/IFFT functions to convert to the time domain. Its departure point is the unloaded launch vehicle accelerances (or receptances) and free accelerations at the payload attachment points. The free acceleration vector are the translational and rotational accelerations at the payload attachment dofs for when the payload is absent (i.e. unloaded launch vehicle).
    - Residual vectors and modal truncation (new): Residual Vectors, sometimes called Modal Truncation Vectors method is included in the handbook, which addresses issues associated with truncating normal modes in structural dynamic analysis, at both the system and component level.
    - Hydroelastic and sloshing waves in tanks (new): When slosh effects are to be modeled in FEM, and the elasticity of the tank is not significant, a spring-mass or pendulum modeling

  is appropriate. A special form of FEM analysis, used for hydroelastic modeling, represents an incompressible liquid and the coupling between liquid pressure and tank wall elastic deflection are provided in the handbook.
  - Generalized modal shock spectrum procedure, severity equation, and Morse chart: Shock and vibration environments produce dynamic stresses which can cause material failure in structures. The potential failure modes include fatigue, yielding, and ultimate stress limit. A severity limit for equipment in terms of pseudo velocity is included in this section of the handbook.
  - Modal tests: Modal testing is usually performed to experimentally validate the dynamic characteristics of components and full system assemblies. Validation of analytical predictions can be achieved using modal test results when a finite element model is being used for predictive purposes. The model deficiencies in the areas related to stiffness of structural joints and fittings that may lead to poor mode predictions or missing modes, which in turn lead to poor loads predictions are discussed in some details in the handbook.
  - High-frequency analysis (new): A detailed discussion of the Coupling Loss Factor Measurement, Damping Loss Factor Theory, Finite Element Method (FEM), Boundary Element Method (BEM), and hybrid methods are provided. The FEM can also be applied to the modeling of acoustic spaces. A popular alternative to finite element modeling of acoustic spaces is BEM. A BEM represents a 3 dimensional acoustic space using a mesh of the surface of the space. This greatly simplifies the challenge of meshing and can be more numerically efficient than a finite element based approach. A general hybrid modeling methodology has been developed that allows all FEM, BEM, and SEA to be coupled together. Using this technique, it is possible to develop mid- to high-frequency models of complex systems such as launch vehicle and spacecraft/launch vehicle that retain details where necessary, while representing other regions of the system with simpler SEA models.
  - Structural damping (new): Loads and dynamics analysis depends on the model parameters of mass, stiffness, and damping and on the forcing functions. Mass is usually well known through design and verifiable via static or dynamic testing. Stiffness is verified through modal testing and updated through flight data. Forcing functions are defined through ground testing. Historically, much effort has been spent on characterizing damping, but most often tested damping values are replaced by a standard value such as 1% modal damping. This is of great importance since damping has a bigger impact on response than any of the other three inputs. Obtaining accurate damping estimates prior to flight is critical for flight success. A new section on damping estimate for different forcing functions and structures are briefly discussed in the handbook.
  - Updated references.
- Section 6: The following new sub-sections are added or significant modification are made to the exciting sub-sections:
  - Envelop limits.
  - Normal tolerance limits: an alternative approach is recommended to derive a P95/50 Maximum Predicted Environment (MPE) level.
  - Mass loading (new): Vibration response of the vehicle structure with a light weight equipment approaches the vibration response of the vehicle structure without the equipment item present. Hence, a light weight equipment item mounted on a heavy structure will generally see about the same vibration environment as measured on the

    structure at the equipment mounting points without the equipment present. However, a heavy equipment item may substantially reduce the structural vibration at the equipment mounting points, particularly at the resonance frequencies of the equipment where the driving point apparent weight dramatically increases. Unfortunately, this reduction in the vibration input to equipment items, particularly at their resonance frequencies, is not accounted for in design or test criteria based upon a computed maximum expected environment that has been smoothed over frequency. Asymptotic Impedances, Barrett method, and most recent development in mass loading of flight structures are discussed in this section of the handbook.
  - Updated force limited methods: New materials related to this method are included in the handbook.
  - Updated references.
- Section 7: The following new sub-sections are added or significant modification are made to the exciting sub-sections:
  - Fatigue under random loadings (new): Flight systems are subjected to loadings that are much more complicated than the periodic loadings used to generate S/N data discussed in this section of the handbook. The challenge is to somehow calculate the damage from these loadings based on the data available from S/N tests. The Time Domain and Frequency Domain approaches can be considered to achieve this. These two methods are briefly discussed in the handbook,
  - Non-Gaussian effects (new): Since fatigue damage accumulation is a significant nonlinear function of stress, therefore, is sensitive to nonlinearity of the loading process. A brief discussion of this method is provided in the handbook.
  - Updated references.
- Section 8: The following new sub-sections are added or significant modification are made to the exciting sub-sections:
  - Design and test criteria.
  - Transient excitation, swept sine excitation, and random vibration excitation: The low-frequency launch environment consists of many different types of dynamic excitations including transient, periodic, and random type waveforms. Ideally, the testing performed to qualify space vehicle hardware for these low-frequency dynamic environments should simulate the basic characteristics, as well as magnitudes and durations, of the dynamic excitations anticipated during flight. However, in many cases it can be very difficult and expensive to be able to directly replicate the complex dynamic environments. Because of this, dynamic testing is often performed using a variety of different input types which in some cases may be derived to result in flight-like responses of the hardware but do not resemble the anticipated dynamic excitations that occur during flight. The different types of test inputs that are used to simulate the dynamics environments necessary to qualify space vehicle hardware are discussed in this section.
  - Modal mass acceleration loads analysis methodology (new): The Modal Mass Acceleration Curve (MMAC) loads analysis methodology was developed to provide the spacecraft limit design loads for low frequency (<100 Hz) dynamic launch environment. It utilizes the Coupled Loads Analysis (CLA) results to calculate an upper bound for the accelerations, displacements and loads for a spacecraft. In this section of the handbook the MMAC method is discussed in some detail.

  - Uncertainty Factor: Uncertainty factors (UFs) are important factors in design load cycles. Unlike safety factors, allowable, and statistical enclosure levels, UF are typically not project requirements. Therefore, UFs are not required and they serve as a viable risk reduction technique that can be used to reduce the risk that downstream changes will cause redesigns or will require waivers. A brief discussion of the UFs is provided in this section.
- Sections 9: An update on shaker technology is provided in this section.
- Section 10: The facilities and procedures used to perform qualification, acceptance, and protoflight dynamic tests on space vehicle hardware are conveniently divided into five categories, namely, those facilities and procedures appropriate for (a) low frequency vibration tests (random and sine), (b) low frequency transient tests, (c) high frequency vibration tests, (d) high frequency transient tests, and (e) acoustic tests. Updates in these forms of testing are discussed in the handbook.

SUMMARY

A community wide contribution was provided from experts within NASA centers and from the space industry to revise the NASA handbook 7005. Many advances made to the discipline over the last several years are included in the revision of the handbook. Also clarifications are made to some of existing materials to remove misinterpretation often made by some users. In this paper the status of the revision of the handbook is provided. We anticipate to complete the revision and get it through NASA Agency wide review within the next few months.

ACKNOWLEDGEMENT

The author would like to thank all the contributors shown in Table 1 of the paper. The author also would like to thank David Oberhettinger of the JPL's Office of Chief Engineer and Paul Gill of the NASA's office standard for funding to revise this handbook. This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

1. Kolaini, Ali R. Doty, Benjamin J. "Statistical Analysis of Extreme Peaks in Random Vibration Response Data." NASA JPL. June 26-28 2007.
2. Scharton, Terry. Pankow, David. Sholl, Mike. "Extreme Peaks in Random Vibration Testing." Cal NC State. June 27-29, 2006
3. NASA-STD-7001 "Vibroacoustics Test Criteria",
4. NASA-HDBK-7003 "Pyroshock Test Criteria".

BIOGRAPHY

Dr. Ali R. Kolaini has been a Member of the Technical Staff at JPL since 2005. He is a Principal Engineer and is the group supervisor of the Dynamics Environments group of the Mechanical Systems Division. Prior to joining JPL, Dr. Kolaini was an Engineering Specialist at The Aerospace Corporation, an associate professor at the University of Mississippi. He has a B.S. degree in Mechanical Engineering from the Lawrence Tech University, and a M.S. and a Ph.D. in Mechanical Engineering from the University of California, Santa Barbara. He has near 30 years of experience in the fields of vibration, shock, and acoustics.