Human Issues related to Spacecraft Vibration during Ascent

Consultant Report to the Constellation Program Standing Review Board

Jonathan B. Clark M.D., M.P.H.

Suite NA 425
One Baylor Plaza
Baylor College of Medicine
Houston TX 77030-3498

1731 Sunset Blvd
Houston TX 77005

713 859 1381
281 989 8721

Jclark1@bcm.edu
jbclark@pol.net

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Opinions expressed herein are those of the author and do not reflect the views of the National Space Biomedical Research Institute (NSBRI), Baylor College of Medicine (BCM), the University of Texas Medical Branch (UTMB), or the National Aeronautics and Space Administration (NASA).

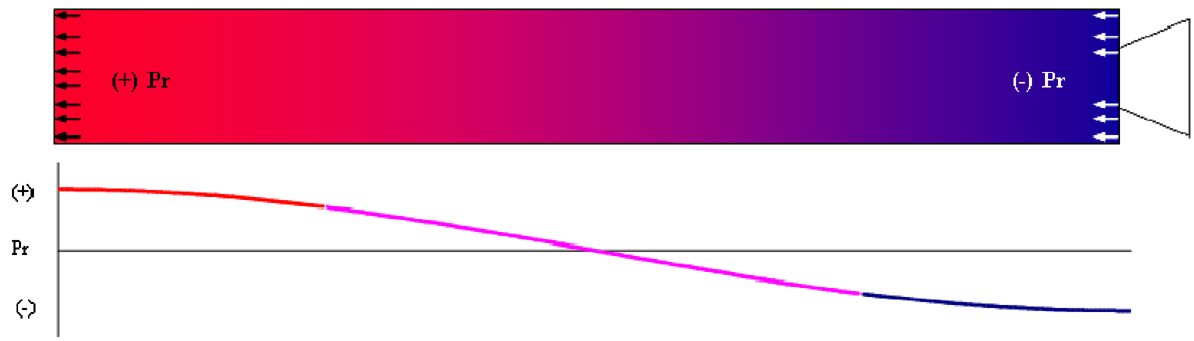
Pogo in Liquid Fueled Rocket Motors

The pogo phenomenon, or fuel pump inlet pressure fluctuation/ cavitation due to tuning feed line resonant frequencies was a major concern in the early space program. Pump tests showed that as inlet pressures were reduced toward cavitation, the pump started acting as an amplifier, causing large oscillations in the thrust chamber pressure. As the rocket engine thrust develops, liquid propellant is cyclically forced into the turbopump. This fluctuating fluid pressure is converted into an unintended and variable increase in engine thrust, with the net effect being longitudinal axis vibration that could result in spacecraft structural failure. In addition the sloshing of liquids in the fuel tanks could also augment the pogo effect. Various engineering controls were used to mitigate this, including pump pressure accumulators and intra-tank baffles. Apollo Saturn V had an ascent oscillation at 11 Hz mitigated to 0.14 g (zero to peak).

Solid Rocket Motor Thrust Oscillation

Thrust oscillation, also called resonant burning, is a phenomenon characterized by increased acceleration pulses that may be felt during the latter stages of solid rocket motor powered flight. Thrust oscillation occurs when a standing wave develops in an open ended tube, like when a solid rocket motor casing expends propellant. It is compounded by the mass and length of the entire spacecraft, in this case exciting a tuned frequency response in the upper stages, building to its maximum immediately before staging. Depending on the pulse amplitude, the impact on vehicle structure and crew may be significant. Thrust oscillation is a characteristic of all solid rocket motors including the first stage of the Ares I launch vehicle. Vortices create inside the solid rocket motor by the burning propellant or other flow disturbances, can coincide, or tune, with the acoustic modes of the motor combustion chamber, generating longitudinal forces. These longitudinal forces may increase the loads experienced throughout the vehicle stack during flight, and may exceed allowable loads on the vehicle and crew. Ascent vibration may also be influenced by aeroacoustic loads.

- In a long cylindrical motor, the 1st longitudinal (1-L) acoustic mode end pressures act together as an oscillating thrust



- Thrust oscillations are determined from axial areas acted on by the motor pressure oscillations
- The oscillation frequency is based on motor gas properties and length
  - 4 segment RSRM → 1-L at 15 Hz
  - 5 segment ETM-3 → 1-L at 12 Hz (because it is a longer motor)

Factors related to Human Effects of Vibration Exposure

1. Vibration environment (how much, when, how long, in what directions)
2. Tasks to be performed during vibration exposure
3. Characteristics of occupant interfaces (seat, restraints, apparel, helmet)

Vibration Effects on Humans

The human body is a dynamic system that is specifically sensitive to low frequency vibration below 20 Hz. The three limits for exposure to low frequency vibration are for 1) preserving comfort (symptom tolerance), 2) working proficiency (performance), and 3) safety (health). These limits define what are called the reduced comfort boundary, the fatigue-decreased proficiency boundary, and the permissible exposure limit. Numerous studies have demonstrated that the seated whole-body has a natural resonance frequency in the vicinity of 4 to 8 Hz during vibration exposure body. Body parts are differentially susceptible to vibration based on the mass and elasticity of the surrounding body tissue. For this report small "g" is used for vibrational g loads (applied input forces) and capital "G" for linear acceleration G force. For some vibration studies the level is described as peak to peak, others use Root Mean Square (rms) which is .707 times peak to peak level.

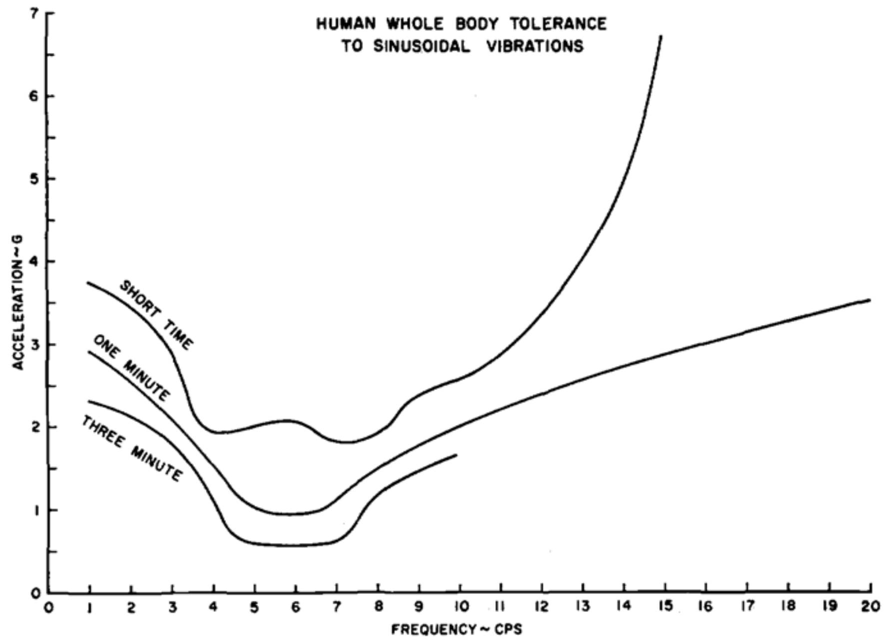
Body-Part Resonant Frequencies (1-G Bias)

Body Component	**Resonant frequency (Hz)**
Whole body, standing erect	6 & 11-12
Whole body, standing relaxed	4-5
Whole body, (transverse)	2
Whole body, (sitting)	5-6
Head, sitting	2-8
Eye ball	40-60
Eardrum	1000
Head/ shoulder, standing	5 & 12
Head/ shoulder, seated	4 -5
Shoulder/ head, transverse rib	2-3
Main torso	3-5
Shoulder, standing	4-6
Shoulder, seated	4
Limb motion	3-4
Hand	1-3, 30-40
Thorax	3.5
Chest wall	60
Anterior chest	7-11
Spinal column	8
Thoraco-abdominal viscera (semi-supine)	7-8
Abdominal mass	4-8
Abdominal wall	5-8
Abdominal viscera	3-3.5
Pelvic area, semi-supine	8
Hip, standing	4
Hip, sitting	2-8
Foot, seated	>10

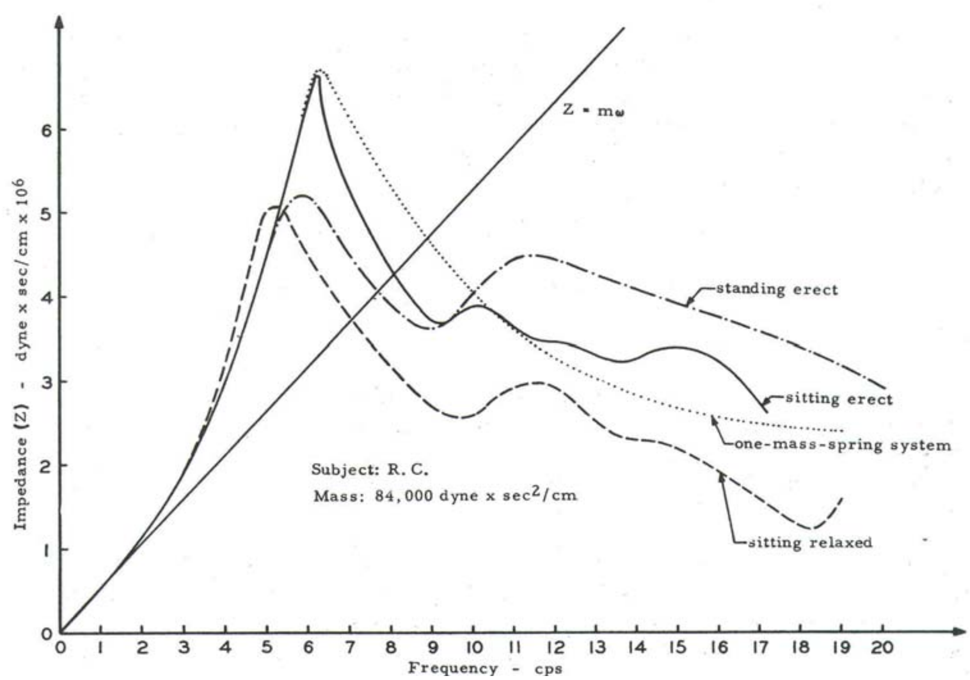
Discomfort Symptoms for Different Vibration Frequencies

Symptom	**Frequency (Hz)**
Motion sickness	0.1 -0.63
Abdominal pain	3 -10
Chest pain	3 -9
General discomfort	1 -50
Complaints	4 -8
Musculoskeletal discomfort	3 -8
Head symptoms	13 -20
Lower jaw symptoms	6 -8
Influence on speech	13 -20
"Lump in throat"	12 -16
Urge to urinate	10 -18
Influence on breathing	4 -8
Muscle contractions	4 -9
Testicular pain	10
Dyspnea (shortness of breath)	1 -4

Whole-body vibration exposure guidelines have primarily been developed for transportation vehicle vibration for exposures from hours to days, with repeated exposures. One study evaluated human tolerance to brief vibration exposures of short time (seconds), one-minute, and three-minute tolerances of military volunteers exposed to sinusoidal vertical vibration in the seated upright posture (Magid et al, 1960). The most critical region is below 10 Hz, with the least tolerance to vertical whole-body resonance between 4 and 8 Hz. These tolerance curves, along with other subjective and psychophysical studies have been used to develop the frequency weightings in current standards. The three-minute tolerance is about 0.5 g between 5 and 7 Hz; the one-minute tolerance is around 1 g and the short time tolerance is around 2 g. The maximum one-minute tolerance occurs at 20 Hz and is approximately 3 g. For short time exposures, vibration tolerance is greater at higher frequencies.

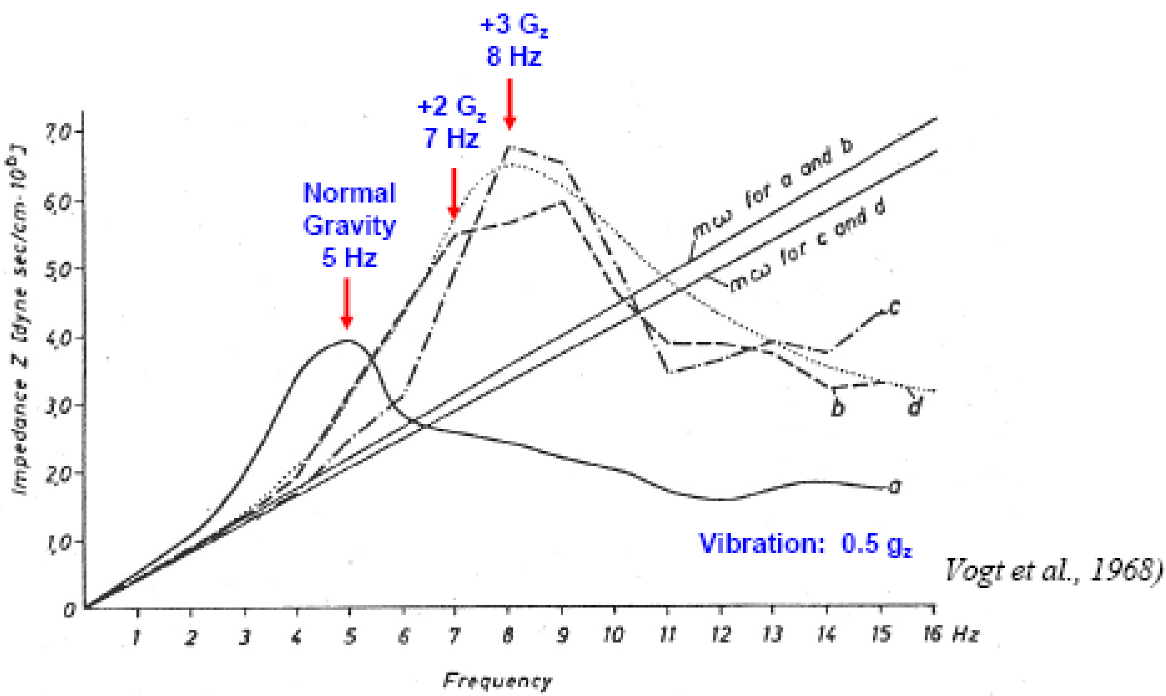


The peak magnitude and frequency of the whole-body vibration response depends on body posture and whether one is standing or sitting. Whole body resonance is primarily related to response of the upper torso and shoulder girdle, including thoraco-abdominal soft tissues and organs. Secondary peaks are associated with the response of other body regions. Most of the performance literature is for upright body posture and G_z vibration (head to toe). This chart shows vibration measured as driving-point impedance, or the ratio between the transmitted force at the point of load application (buttocks in the sitting posture) and the input velocity for several postures (Coermann, 1961).



G-loading alters the human vibration response
Most human vibration studies have been conducted under normal gravity. The resonant frequency of the human body shifts to a higher frequency with increasing sustained acceleration, which may be due to a stiffening of the body under higher G. In normal gravity, the body's resonant frequency shifts downward with increases in vibratory load. During a spacecraft launch, occupants are exposed to vibration and sustained acceleration. G loading dramatically changes the vibration susceptibility of body parts because compression along the acceleration axis reduces compliance and increases stiffness.

Effect of Vibration and Acceleration Axis
Using a vibration table mounted on a centrifuge, Vogt et al. (1968) evaluated the driving-point impedance during exposures to 0.5 g_z head to toe vibration with +2 and +3 G_z (eyeballs down) sustained acceleration. The impedance magnitude and impedance frequency increased with increasing sustained acceleration, shifting from 5 Hz during normal gravity to 8 Hz at +3 G_z sustained acceleration.



Vogt et al. (1973) investigated the effects of sustained acceleration in supine subjects (Eyeballs in). The vibration was held at 0.4 g_x with sustained acceleration from 1-5 +G_x (relative to the body axis). The resonance of the supine human body increased from 6 Hz under normal gravity, to 8 Hz at +2 G_x, to 11 Hz at +3 G_x, to 13 Hz at 4 +G_x, and 15 Hz at 5 +G_x. The impedance magnitude also increased with increasing sustained acceleration.

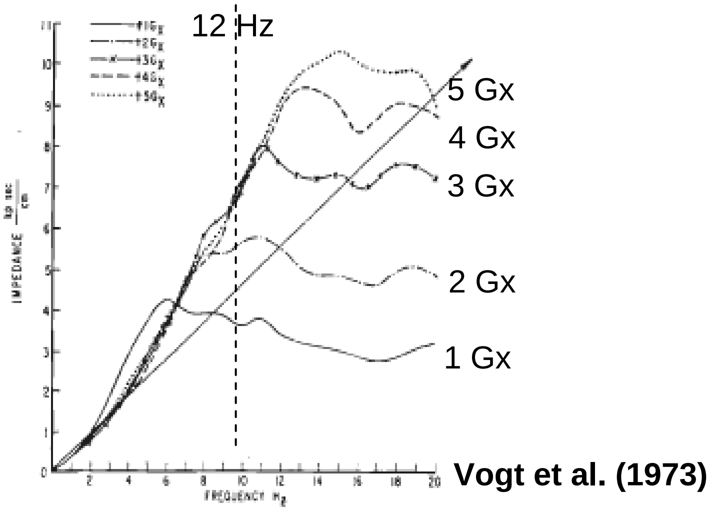


Figure 2. Mechanical Impedance for $1G_x$ — $5G_x$ Sustained g, Plotted vs. Frequency.

Visual Performance and Vibration

Vibration causes degradation of vision due to movement of the image on the retina. Movement of the retinal image can occur due to vibration of the observer, the display, or both. Only the central 2 degrees of the retina (the fovea) can see a 20/20 visual acuity (2 degrees is the width of the thumb at arms length). With vibration the image continually moves to a different part of the retina and the image becomes blurry. At an oscillation frequency of less than 1 Hz the eyes can compensate by using slow (smooth pursuit) eye movements, at 1-2 Hz the eye uses quick (saccade) movements to compensate with some success, but above 2 Hz the saccades are not fast enough to compensate and the image will be no longer be clear. With higher frequency vibration, the increasing phase differences between display and eyes will increase visual degradation. Higher frequency vibration is dampened by the body. If vibration reaches the head or the head is in contact with the vibrating structure/ headrest, visual blurring is due to eye resonances, which occurs at 40-60 Hz.

Manual Performance and Vibration

Manual control errors increase between 2 and 16 Hz at 0.05 g_z in the vertical axis with the worse case near whole-body resonance (4-8 Hz). Manual control is seriously affected above about 0.25 g_z (vibration in the vertical body axis or head to toe). The largest error in fore-and-aft (X) and lateral (Y) directions is at 1.5 - 2 Hz. Low frequency vibration can produce vibration feed-through to the control stick. Error depends on specific details of control task. Tracking task performance under vibration was better with isometric (force) control levers than with force-free isotonic (displacement) control levers. Spacecraft vibration is often complex multiplanar while lab studies often use a single axis rhythmic oscillation (sinusoidal). Generally sinusoidal vibration degrades performance more than non sinusoidal (sum of sines) vibration. Human vibration effects vary with vibration axis with respect to the subject's alignment. G_x (eyeballs in/out) is generally less degrading than G_z (eyeballs up/down) or G_y (eyeballs left/right).

Sensitive Vibration Frequencies Affecting Human Performance

Activity	**Frequency range (Hz)**
Equilibrium	30 – 300
Tactile sense	30 – 300
Speech	1 – 20
Head movement	6 – 8
Reading (texts)	1 – 50
Tracking	1 – 30
Reading errors (instruments)	5.6 - 11.2
Manual tracking	3 – 8
Depth perception	25 - 40, 60 – 40
Hand grasping handle	200 – 240
Visual task	9 – 50

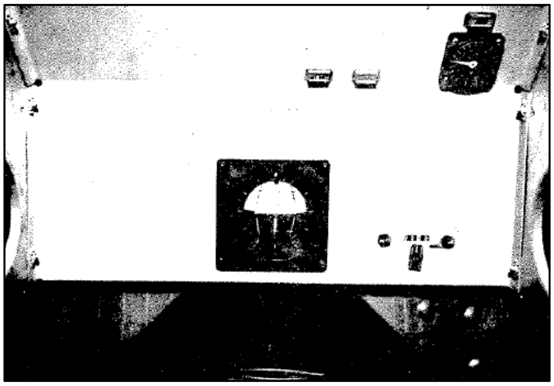
Vibration Aftereffects

Although there are no formal studies of vibration aftereffects, there is an anecdotal report by Faubert et al. (1963) of perceptual and performance aftereffects for g_x vibration at levels below the health limit. Infrequently, a headache or sore neck persisted beyond the immediate post-exposure period for 12 to 24 hours, and rarely, for longer periods.

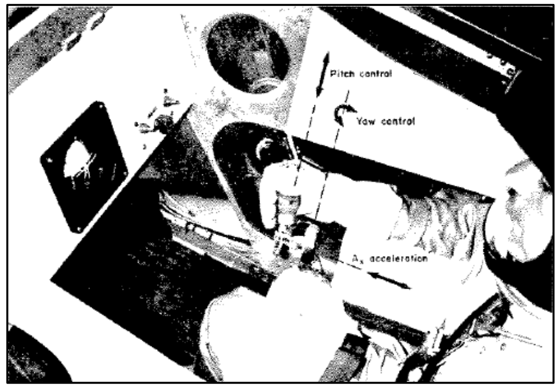
Vibration Studies in Support of Early US Space Program

Human vibration studies in support of the Mercury, Gemini, and Apollo programs were conducted at Wright-Patterson Air Force Base (WPAFB) and Ames Research Center (ARC). Display readability in the semi-supine (recumbent) position during x-axis (sternum-to-spine) vibration was evaluated for several vehicle seating configurations by Taub (1964), Faubert, Cooper, and Clarke (1963), Shoenberger (1968), and Clarke, Taub, Scherer, Temple, Vykukal, and Matter (1965). Subjects read displays during 11 Hz vibration to assess accuracy (error rate) and response time. The Gemini Prevention of Coupled Structure Propulsion Instability (POGO) project determined acceptable visual performance vibration limits in a Gemini part-task simulator on a combined centrifuge and vibration facility at Ames Research Center. At 3.5 g_x sustained acceleration at 11 Hz vibration, pilots deemed their performance of fine-scale visual tasks (reading analog dial-meters and digital timers) to be satisfactory at 0.25 g_x (0 to peak, eyeballs-in) for the 11 Hz vibration. These studies demonstrated that at 11 Hz vibration, visual acuity was degraded in the range of 0.14 – 0.3 g_x, and severely degraded beyond 0.7 g_x (Vykukal & Dolkas, 1966). Body resonance was occurred around 6 Hz at +2.5 and + 4 G, and increased at higher frequencies, the highest impedance occurring at higher G level. At 2.5 G, subjects reported stomach vibration between 9.5 and 12.5 Hz. Double vision was reported at 14-16 Hz. Increased sustained acceleration increased pain awareness at measured resonances (7, 11, 18 Hz).

Gemini Mockup Instrument Panel



Pilot using controller and display



Gemini/ Apollo astronaut Frank Borman provided perspective about his experience as a vibration test subject in the journal Aerospace Medicine (December 1964, page 1160-1). *"During the past year I participated in a program at Ames Research Center which was designed to investigate pilot capability to function during 11 cycles per second longitudinal accelerations. This was the familiar "pogo" problem we encountered on the Titan II. Several hazardous duty personnel had already ridden the centrifuge when I arrived, and I was assured by all of them that the program was "no sweat"-they could all take a very high level of acceleration. All of these test subjects were young, vigorous, non-rated Air Force personnel. The program to them was almost a competitive experience to see which could stand the highest level of vibration and survive. Those of us from the Manned Spacecraft Center who rode the centrifuge came up with an acceptable "g" level very much lower than was tolerable to hazardous duty people. I'm afraid this disappointed the people running the test, but they should have expected the result. We were looking at the vibration problem from the pilot's stand point of how it would affect our performance during launch, not whether we could experience the vibration and survive."*

Performance Rating (Modified Cooper Harper) for 11 Hz g Vibration

3.5 g_x (Eyeballs-In) Bias - Gemini Displays and Tasks

Activity	Pilot Rating at Various Vibratory G Levels				
	0.14	0.30	0.53	1.36	1.65
Read Rate Needles	2	4	6	8	9
Read Digital Timer	2	5	6	9	10
Read Accelerometer	2	4	5	8	9
Actuate Booster Shutdown	1	2	3	4	6
Actuate Secondary Guidance	1	2	3	4	6
Ability to Speak	1	3	4	7	9
Ability to See Abort, Guidance, and Overrate Lights	1	2	3	4	5
Actuate Toggle and Current Breaker Switches	3	4	6	8	9
* Ability to Read Cabin ECS, Fuel Cell, and Propellant Pressure	2	4	5	8	9
* Adjust Suit Flow Controls	2	3	5	8	9
* Ability to Read Launch Attitude Error	2	4	6	8	9
* Masking of Other Critical Vibration and Booster Motion Cues	3	4	7	9	10
Overall Average Rating	1.8	3.4	4.9	7.1	8.3

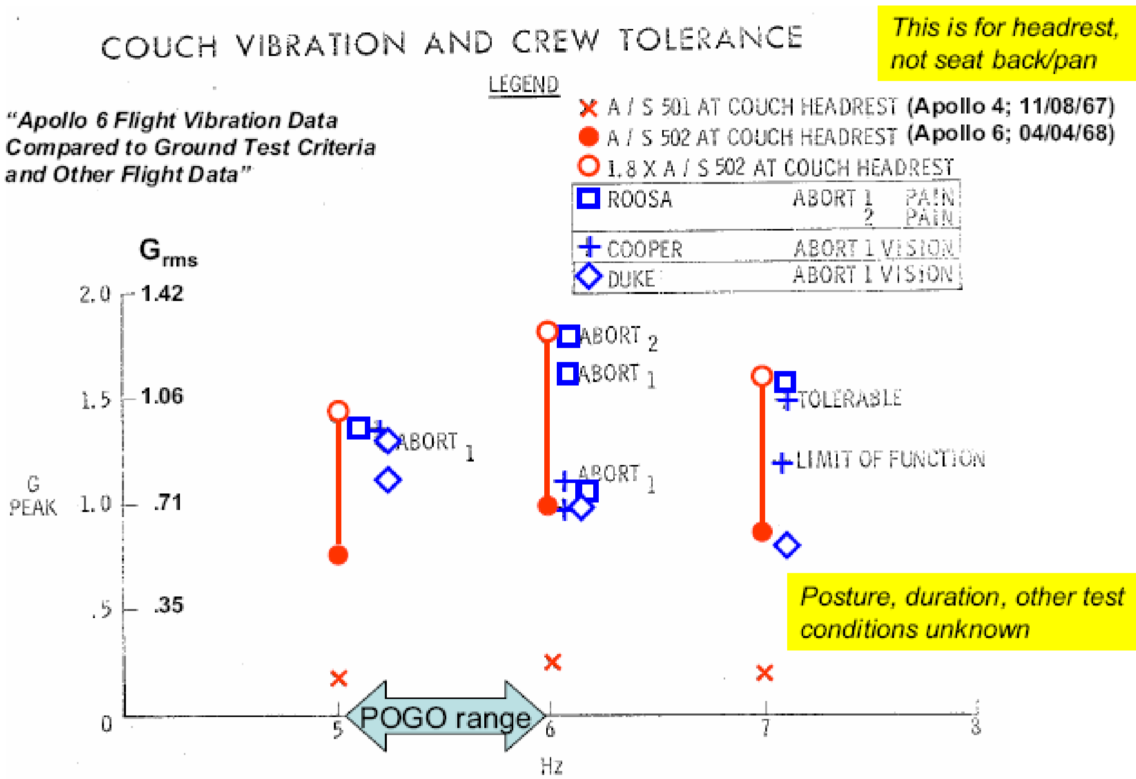
* Corresponding Display and Controls not included in Simulation, Estimated Effect of Vibration

Pilot Rating Scale

Effect of Vibration	Pilot Rating
No Effect	1
Slight Degradation	2,3
Moderate Degradation	4,5,6,7
Severe Degradation	8,9,10

Performance Ratings for 11 Hz g_x under varying vibratory g levels (Vykukal & Dolkas, 1966)

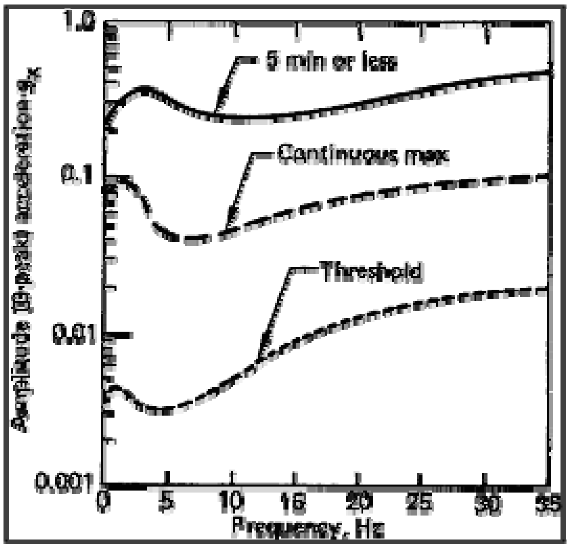
This study revealed that at 11 Hz vibration frequency in the range of 0.14 – 0.3 g_x peak to peak, visual acuity noticeably degraded with vibration, with severe degradation of visual performance occurring beyond 0.7 g_x peak to peak.



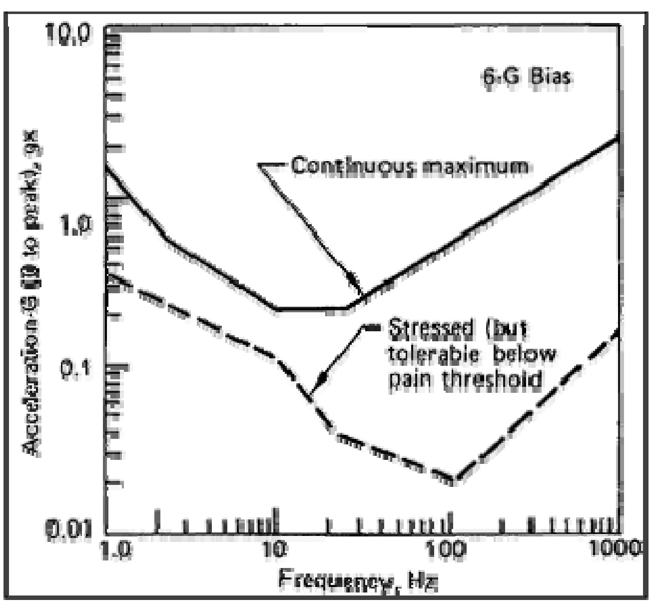
Apollo Command Module couch launch data (North American Rockwell Space Division Report SID 64-1344C) indicated vibration levels of 0.77 g_x rms at ~90 sec following lift-off and lasted less than 10 sec. The worst 1-minute interval occurred from 50 to 110 sec following Apollo lift-off for an average vibration level of ~ 0.3 g_x rms at the couch.

NASA Standard 3000

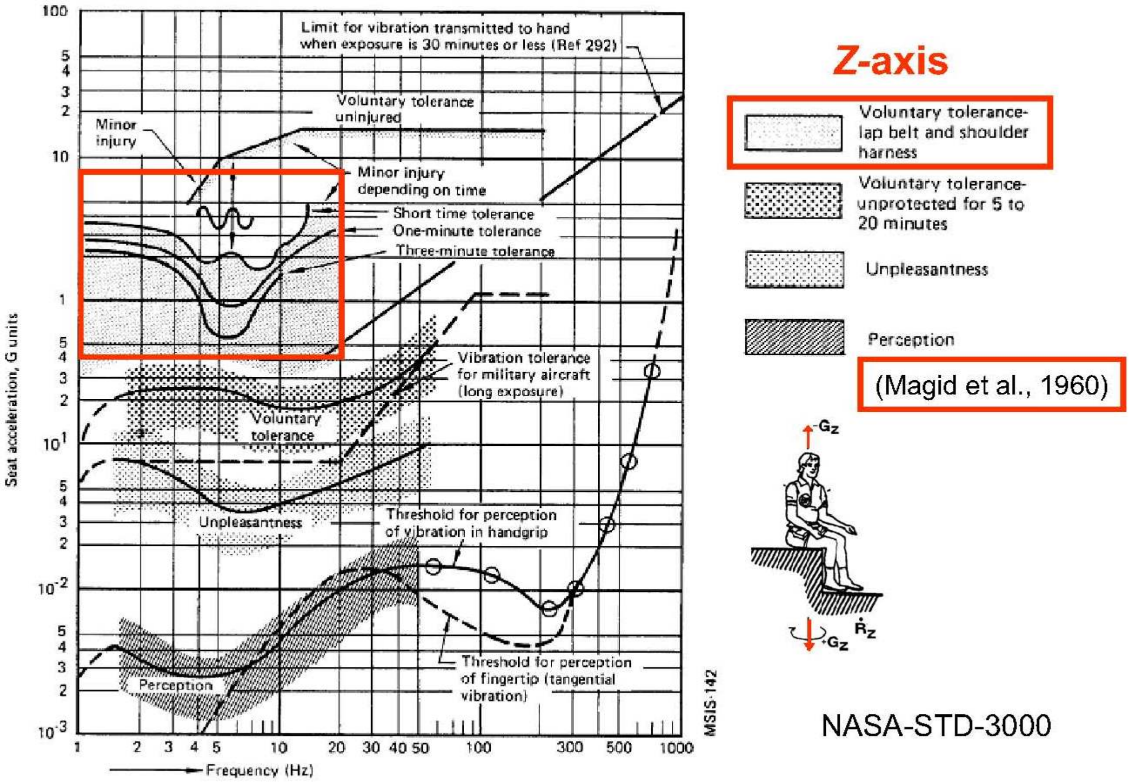
Data from the Gemini and Apollo vibration under sustained acceleration studies was compiled in the Bioastronautics Data Book. This formed the basis for the Manned System Integration Standard (MSIS) or NASA Standard 3000. NASA Standard 3000 has evolved into the Human Systems Integration Requirement (HSIR).



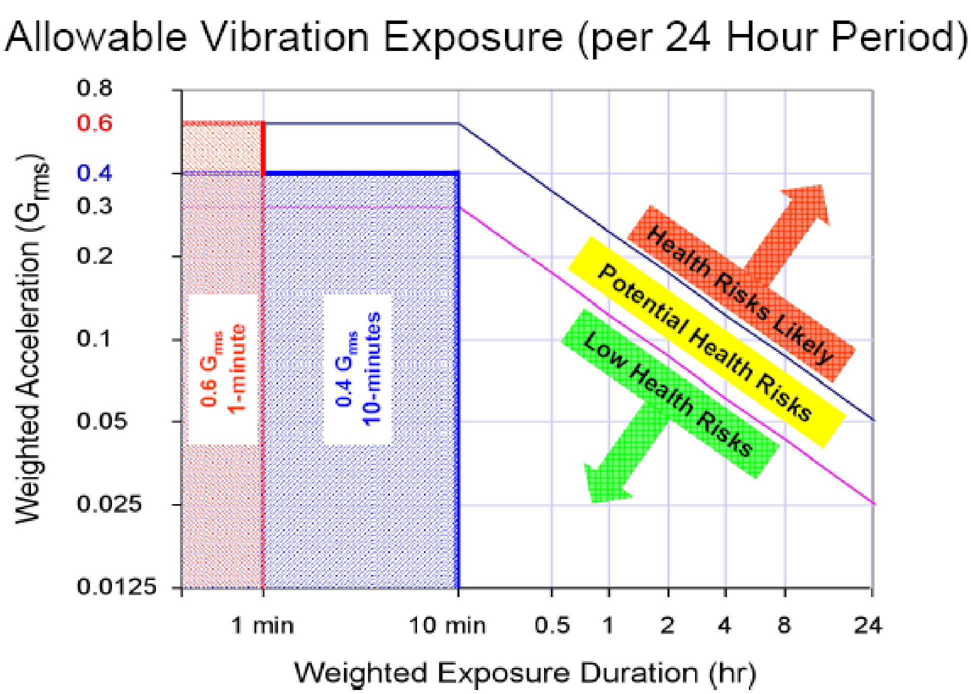
Tolerance Limits to Equivalent Sinusoidal Vibration (g_x) for Visual Monitoring of Critical Displays During Launch



Maximum Tolerable Limits of Vibration (g_x) for Visual Activity and Toggle Switch Manipulation During Launch



The International Standards Organization ISO 2631-1 has developed a health-risk boundary for upright body posture (1-G_z head-toe bias) and g_z head-toe vibration for short and long duration exposure.



From ISO2631-1 Figure B.1 "Health guidance caution zones"

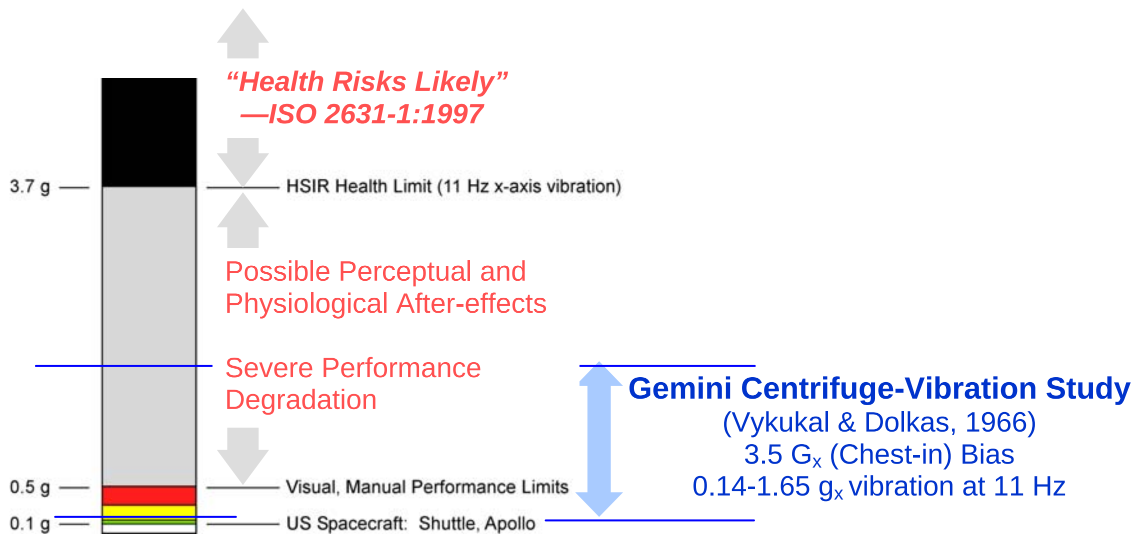
Constellation Program Human System Integration Requirements (HSIR) Vibration Health Limits
HSIR Revision B, CxP 70024 Release Date: 03/03/08
Note HSIR Rev C is in the approval process with release expected in November 2008.

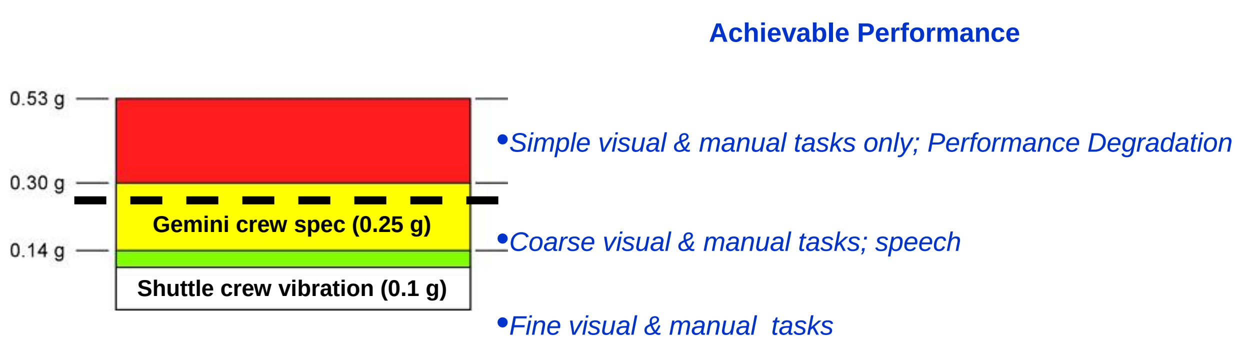
HSIR Wording on Vibration

3.2.5.1 Health Limits for Vibration

[HS3105] The Constellation Architecture shall limit vibration to the crew in any axis to less than 0.6 g rms integrated from 0.0167 to 80 Hz over any one-minute interval during dynamic phases of flight.

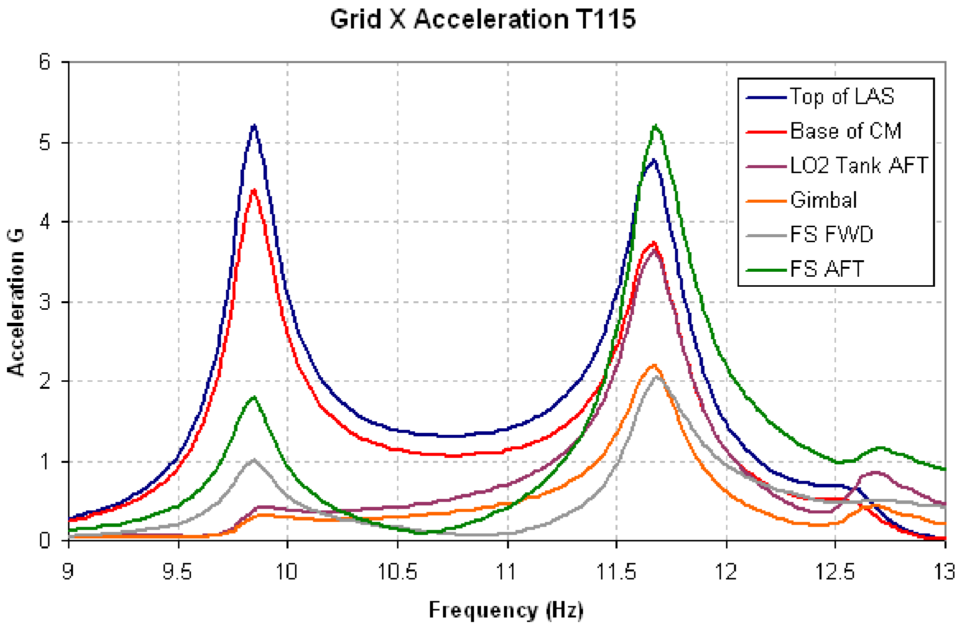
Comment:
HSIR Requirements for vibration is primarily concerned with health limits.





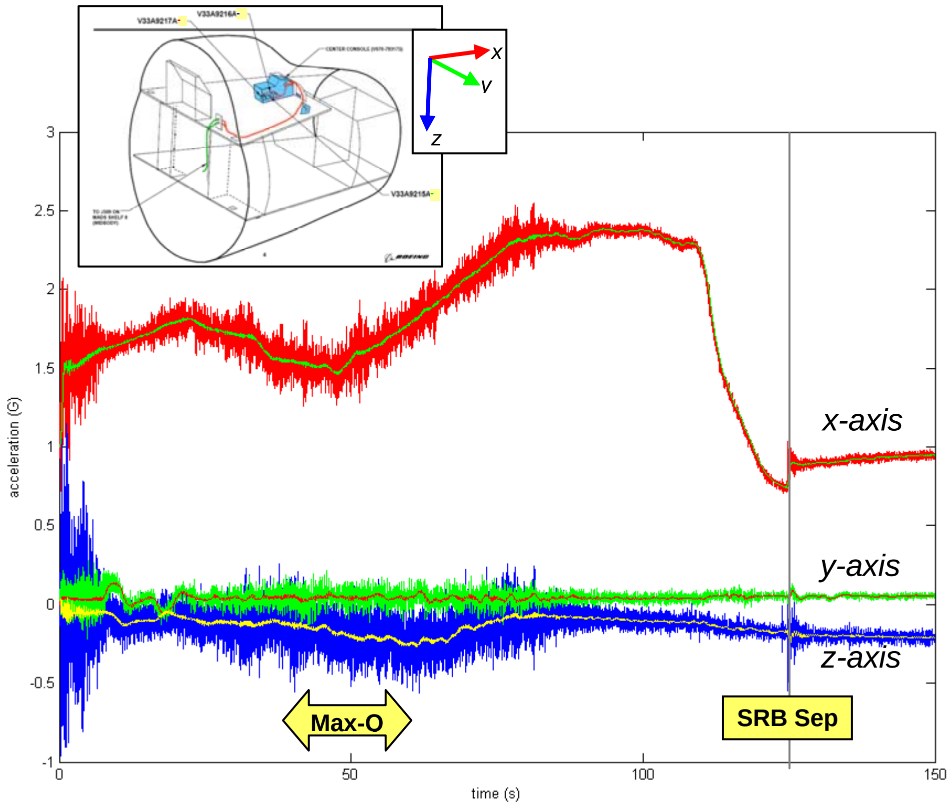
Constellation Program Ares I Ascent Vibration Issues

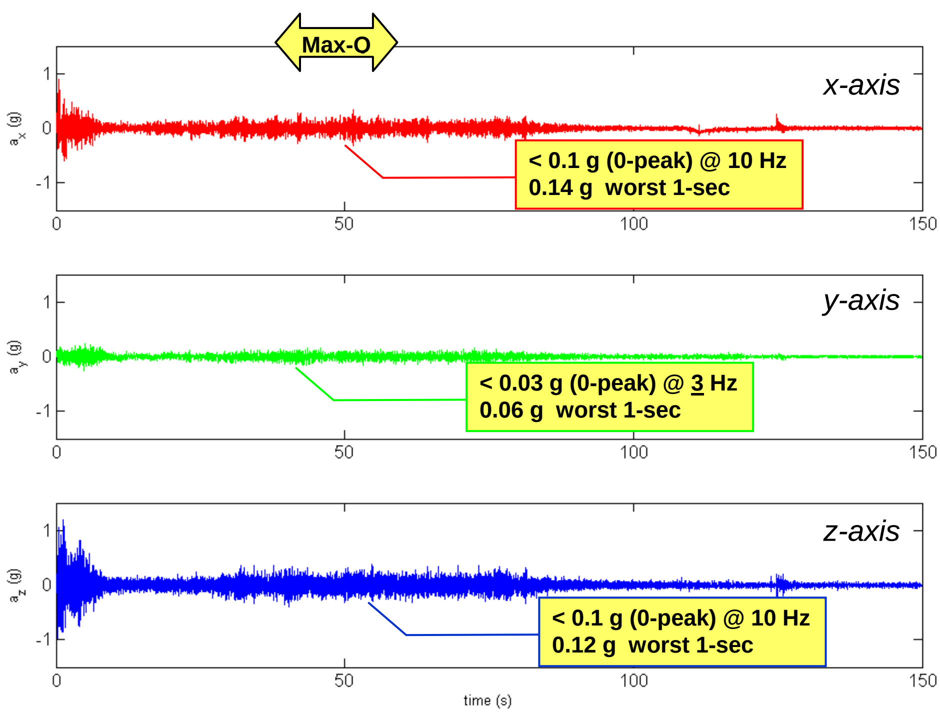
Thrust oscillation modeling of the Ares I ascent during solid rocket motor burn estimated an 11 Hz vibration of 5-7 g_x would be delivered to the crew about 110 seconds into flight. This vibration level is well above the 3.7 g_x human health limit. The max G load during ascent is 3.8 in the longitudinal axis (+G_x or eyeballs in). It is anticipated that thrust oscillation will build up to a maximum over 5-10 second just prior to first and upper stage separation.



In a nominal ascent no crew action is required. At staging the service module (SM) panels separate, the J2 engine ignites and 30 seconds later the launch abort tower is jettisoned. If the SM panels do not jettison, the crew may have to inhibit the launch abort system jettison. If guidance is not converging after J2 engine ignition there is option to initiate a launch abort or take over and fly manually. Although crew performance during the 1st stage abort initiation where thrust oscillation would clearly be a factor, the is also concern about residual performance effects (after-effects) following thrust oscillation, where crew may be required to manually fly the vehicle for the 8 minutes to MECO.

The Crew Office has stated that Constellation vehicles should be no worse than shuttle with regards to vibration and display usability, however the shuttle vibration environment has not been fully characterized. From 5-10 seconds following lift-off through SRB separation, the dominant Shuttle flight deck vibration frequency is 10 Hz in both the x- and z-axes below 0.10 g (zero-to-peak), as measured at the Shuttle flight deck console (STS 114 and 116). Anecdotal non-objectively quantifiable reports from Shuttle crewmembers indicate performance decrements occur during the initial 120 seconds of flight. Shuttle seat vibration levels have not been characterized but will be evaluated as part of an upcoming flight study.

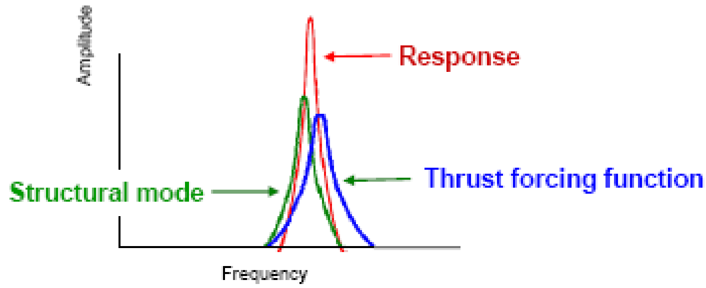




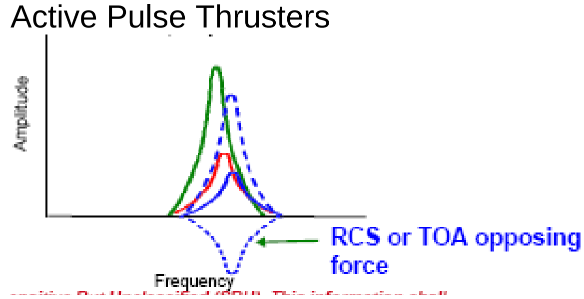
STS 116 Flight Deck Vibration Data

Thrust Oscillation Mitigation Strategies

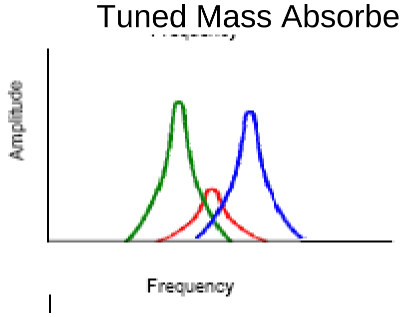
- Eliminate or Reduce Forcing Function
  - Eliminate Thrust Oscillation at the source (SRM design)



- Cancel or Isolate Forcing Function
  - Detune the vehicle 2nd longitudinal modes
  - Increase vehicle damping
- Create an opposing forcing function
  - Active Pulse Thrusters



- Detune Stack Away From Forcing Function
  - Mechanical Isolation (between FS and US, US and CEV)
  - Tuned Mass Absorber



- Occupant Protection and Isolation
  - Isolation of seat or pallet from vehicle
  - Contoured seat
  - Adjustable couch
  - Elastic seat cushions
  - Suspension seat
  - Body restraints
  - Head restraint
  - Vibration absorbent hand/foot rests

Crew Performance Optimization

Displays and Control Design

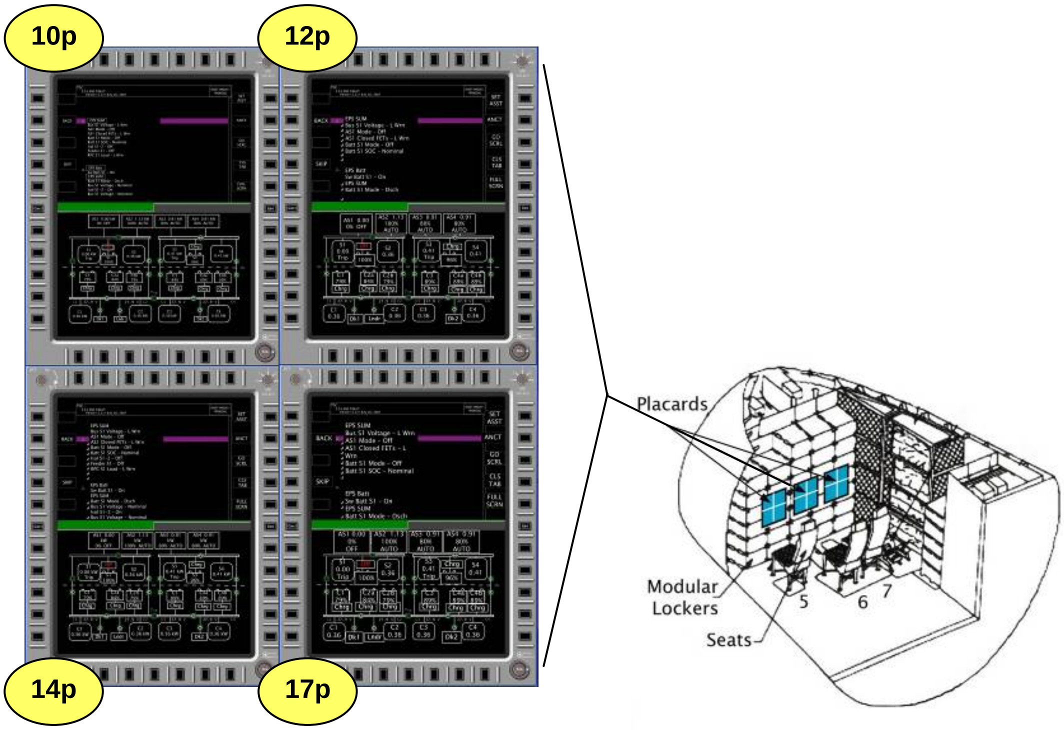
Reduce Conservatism of Vibration Limits

Evaluate historical data and reassess human performance issues

The studies that developed the original human performance limits for spacecraft vibration used Gemini-derived displays (dial gauges, mechanical number wheels, blinking incandescent lamps), a Gemini-like part-task simulation, and a rigid sheet-metal seat. Since Orion will use electronic interfaces such as electronic procedure viewer, interactive virtual (soft) switch panels, and multifunction display (MFD) units, a reassessment of human performance under vibration and acceleration with these new displays and controls will allow a more system specific vibration limit. The crew vibration performance requirement will probably be between 0.1 - 0.5g_x, with 0.25 g_x as the vibration design goal, but may have to be higher if Ares vibration loads and mitigation strategies can not be reduce vibration this low. The decision on the vibration design limit will require human data that tie vibration level, task complexity, and interface design with crew performance to characterize the trade-space. Vibration response is affected by biomechanical impedance which is altered by G-forces, so performance data using Orion like displays and controls with anticipated Ares I G-loading and vibration will provide the most appropriate insight. These are the upcoming studies to address these issues.

Pending Vibration Studies to address Human Health and Performance Limits

Research Project	**Study Description**	**Product**
Detailed Test Objective (DTO) 695	Flight Study (STS 119, 127, 128) Acceleration measurement of Shuttle seats 3, 5, 7 during Shuttle SRB ascent phase Three triaxial accelerometers per seat (seat pan, back/ headrest)	Characterization of Shuttle launch vibration/ acceleration environment
Detailed Supplemental Objective (DSO) 604	Flight Study (STS 119, 127, 128) Effects of Launch Phase Vibration on Visual Performance	Quantitative visual performance assessment during SRB ascent vibration and acceleration Effects of launch vibration impedance (amplification or dampening) between seat and crew on visual performance
Human Research Program Vibration Performance Study	Laboratory Study (Ames Research Center) Reading performance evaluation using Orion-like displays under vibration loads of 0-0.5 G_x at 12 Hz with supine seated test subjects and astronauts (seated lying on back)	Vibration effects on reading performance under 1 g Characterization of vibration induced after effects
Human Research Program Acceleration Vibration Performance Study	Laboratory Study (Ames Research Center) Reading and flight-like procedure performance evaluation under combined G_x acceleration (1, 2, 3, 3.8 G) and G_x vibration (0- 0.7 g rms) with Orion type displays and tasks with test subjects and astronauts	Vibration performance degradation compounded by acceleration Characterization of acceleration vibration induced after effects Recommendations on vibration limits and font size Data to validate vibration transfer function models



Display Placards for the DSO 604 Effects of Launch Phase Vibration on Visual Performance Study

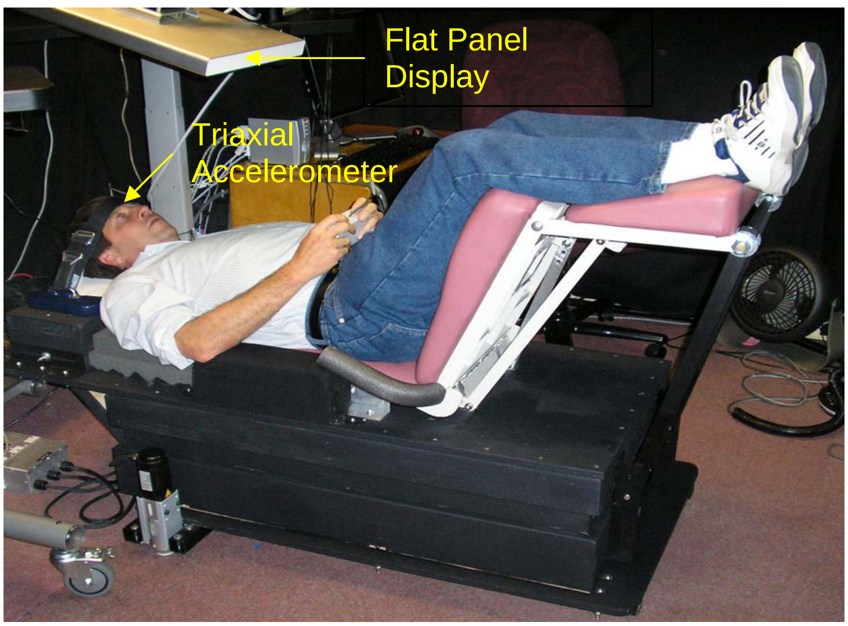
During ascent three mid-deck crewmembers will focus on the placard and signal the quadrant containing the smallest text that is readable during that phase of flight. Pre-liftoff control will be made immediately and continuously throughout ascent.

1. Launch – highest vibration phase, (~10 seconds post lift-off)
2. Pre-max q – the time from lowest vibration after launch until onset of the highest dynamic pressure (q), (~20 seconds post lift-off)
3. Max q – the time of highest dynamic pressure and second highest vibration during the ascent phase of flight, (~50 seconds post lift-off)
4. Post-max q – the time after max q until SRB separation, (~80 – 125 seconds post lift-off)
5. Post SRB separation – the time immediately after SRB separation, lowest vibration during ascent, used as post vibration control data (~130 sec post lift-off)

The goals of the Ames Research Center studies are to:

1. Measure reading error rates and task response time as a function of vibration level using Orion-like visual displays at two candidate text font sizes (10, 14).
2. Determine if there are reading performance aftereffects immediately following cessation of vibration.
3. Compare vibration effects on performance under elevated + G_x -loading (3.8 G_x) with 1 G_x (Earth gravity in a semi-supine position).
4. Measure subjective ratings of display usability for different display formats as a function of vibration at +1.0 G_x and +3.8 G_x in semi-supine position.

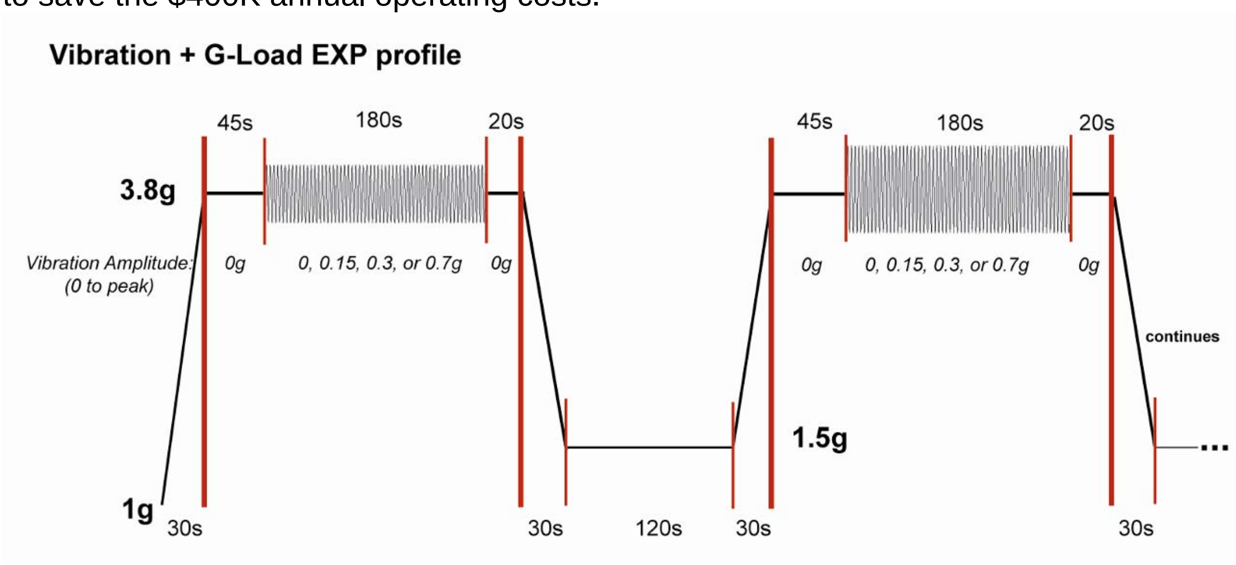
The vibration only and the vibration with centrifugation study will evaluate display readability of a standard LCD screen at 20 inches. The visual task is not just a legibility test, as the subject is required to locate, distinguish, read, and process, hence is more appropriately termed “readability”. The study involves one day of familiarization runs, and a second day of data collection runs.



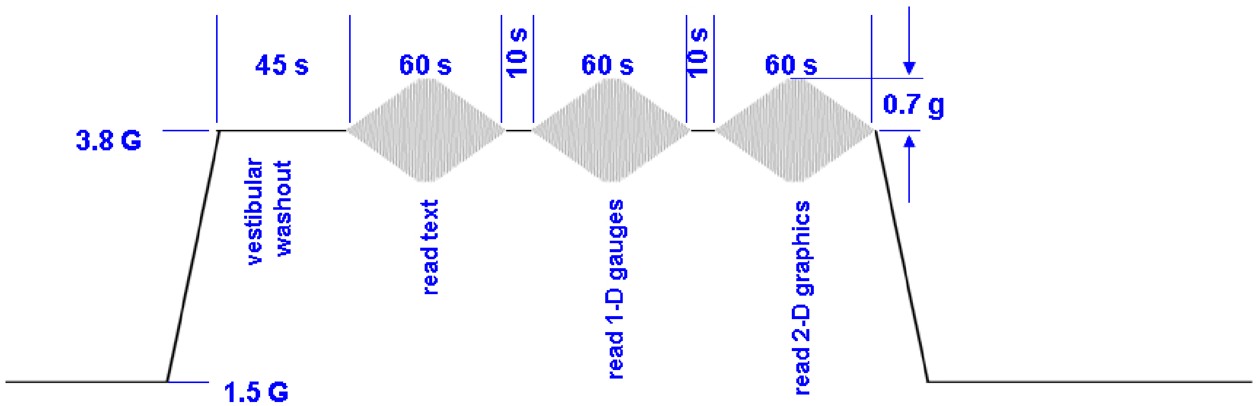
3-Degree Of Freedom Vibration Chair / 1-G_x Bias (seated supine)

Ames Centrifuge
29 foot (8.9 meter) radius centrifuge human rated to 12.5 G, capable of 20 G at 47 RPM
This study will take subjects up to 3.8 G at 20 RPM with transitions of 0.1 G/sec.

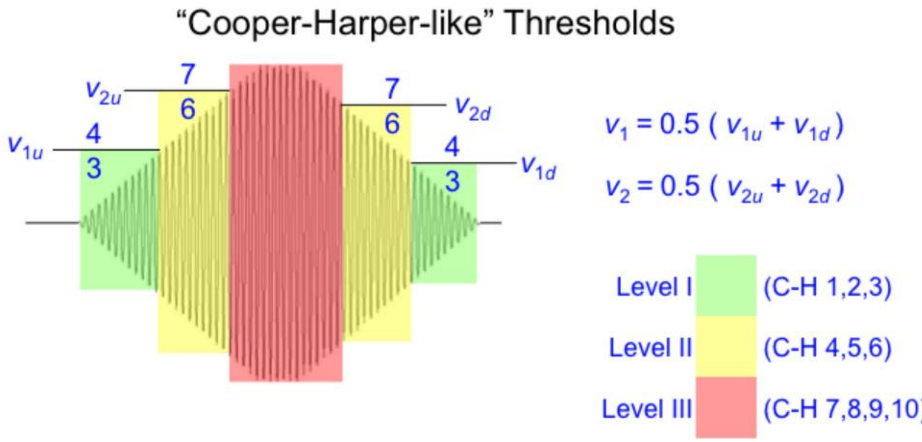
Note: The Ames Centrifuge facility, one of the only places capable of vibration during centrifugation using human subjects, is due to be closed in 2008 or 2009 to save the $400K annual operating costs.



Vibration profiles cover no vibration, and 4 vibration profiles (0.15, 0.3, 0.5 and 0.7) g_x rms (which is .707 of peak to peak) in random order (i.e. not increasing in magnitude). The vibration exposure duration is over several minutes, which is not the duration anticipated for the vibration from solid rocket motor thrust oscillation, (5-10 seconds).



Vibration ramp up/down with visual performance task, will be done at 1 G_x and also 3.8 G_x



Subjects determine when the visual task is easy (green), hard (yellow), and impossible (red) using modified Cooper Harper Ratings during the vibration ramp up and down.

Caveats to Laboratory/ Ground Based Studies

The performance effects can be influenced by the type of measurements that are done. For a laboratory study to have greater operational validity the performance tasks (visual displays, control systems) should be similar to the actual or proposed vehicle hardware. The motion profile (acceleration, vibration, duration, seat interfaces) should be as close to actual parameters as possible. Without an actual ascent vibration profile and vehicle seat system it is only an approximation what the performance impacts will actually be. The effects of vibration can be variable so testing a limited number of subjects in a study is no guarantee that the full consequences will be known. The vibration profiles in the centrifuge vibration study will probably be of longer duration than actual flight. Centrifugation produces angular acceleration in addition to the linear acceleration that is desired. Angular acceleration is an undesired effect that can produce motion sickness which can also affect human performance.

Observations from the Centrifuge Vibration Studies

I observed test subject runs from 15-17 September 2008 on the Centrifuge Vibration study at Ames Research Center. I rode the familiarization vibration centrifuge protocol on 16 September. This involved G only runs at 1.5, 2, 3, and 3.8 G_x for several minutes at each level, a short break then 3.8 G runs with incremental vibration from 0.15- 0.7 g_x rms, sustained vibration, 0.6 g_x vibration for 145 sec, and 3 ramp up/down cycles while interpreting the visual displays. The 3.8 G_x is physically demanding, and difficult to take a full breath. With vibration and reading task above 0.3 g_x it was difficult to impossible for me to reliably interpret visual information. Following the run I was fatigued and felt unsteady but this improved over several hours. I didn't have any motion sickness and was able to eat right after the run. I felt I had returned to pre-baseline normal by 4-6 hours. This may be related to age and physical fitness, as it seemed that younger and physically fit subjects did much better than me.

From 1-3 October 2008 I observed astronaut test subject runs. Tolerance to vibration and centrifugation was variable as was visual performance. Tolerance and visual performance improved from the Familiarization run to the Data Collection run the following day, suggesting adaptation to the combined G and vibration. How long this adaptation lasts is unknown, but veteran astronauts recover from spaceflight better than rookies, even with many years between flights. All the astronaut test subjects felt that having a vibration G exposure prior to actual flight would alleviate the anxiety of the first vibration G experience. Crew developed a variety of adaptive strategies to improve visual performance, such as blinking eyes to reduce blurring, or trying to anticipate or lead the vibration movement. The research study is collecting these strategies as well as the actual performance results and will hopefully release this soon. All test subjects felt that the 0.7 g_x vibration level significantly degraded vision and that making a life and death decision based on that information would be risky. Some crew did amazing well even at 0.7 g_x, only making a few mistakes in the visual task, but still felt their performance was unacceptable. Compared to their spaceflight experience, astronaut test subjects felt that the 0.15 g_x vibration run felt like a Soyuz launch, and the 0.3 g_x vibration run felt like a Shuttle launch. The Shuttle G load of 2.5 is obviously less than in this study (3.8). All test subjects (non astronauts and astronauts) undergo a functional neurologic assessment before and after the runs, and must wait at least an hour in the test facility before returning to work or driving home and may only leave if they are without any symptoms. Following the vibration G runs most subjects were initially unsteady walking heel to toe with eyes closed. Forward bending or pitch head movements were provocative, but other head movement directions were relatively well tolerated. Crew felt that the challenges of the assessment, particularly making provocative movements, actually hastened their recovery. From a symptom standpoint, some crew were able to return to pre-study baseline within half an hour, others not till the following day. Some crew even felt that they could return to crew duties in a T-38 within a few hours.

Concerns for the Effects of Vibration on Human Performance

Crew tolerance and visual performance may be improved by repeated exposure to combined acceleration and vibration.

Adaptation to linear acceleration and vibration may be accomplished by exposure to ground based centrifuge with vibration capability.

Individual variability and motion susceptibility can result in significant differences in performance.

The vibration profile changes between the spacecraft, capsule, seat, seat interface/ suit, restraints, and body torso and head and neck.

Orion crew-seat vibration in x-, y-, and z-axes will have to be characterized and analyzed based on actual flight data (Ares I test flight series).

Nominal and Off-Nominal Crew Tasks during Ascent should consider the nominal and off-nominal vibration and linear acceleration environments

Crew performance will have to be optimized in response to thrust oscillation via seat vibration isolation and display and control force mitigations (larger fonts, arm rests, isometric control levers).

All crew seats should not exceed the vibration performance limits.

For mitigating Thrust Oscillation, isolation of the entire seat pallet may be more feasible than isolation of individual seats.

Thrust Oscillation mitigation strategies may be different for Lunar Capability (4 crew) than for the Initial Capability 6-crew missions to ISS.

Some Thrust Oscillation mitigation strategies may increase risk for occupant protection in other dynamic phases (contingency land landing, nominal water landing).

Summary

The primary human centric issues concerning spacecraft vibration include the vibration characteristics (magnitude, frequency, direction, and duration), vibration transmissivity from the source to the body, individual variability and adaptability, and operator tasks.

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