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A Method for Extrapolating Haversine Shock Test Levels

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Introduction

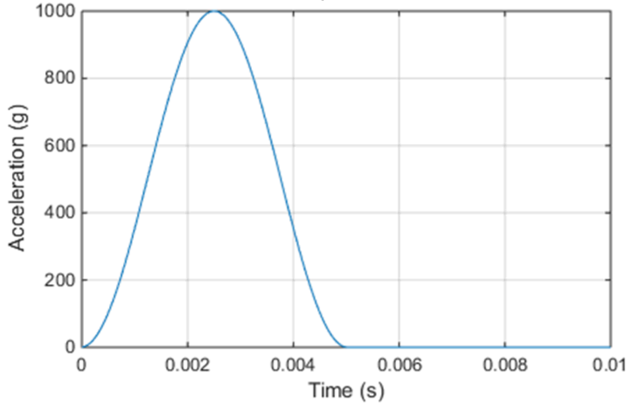
- Field collected shock data is typically simplified for subsequent laboratory testing on standard test machines
  - Drop tables
  - Resonant fixtures
  - Electrodynamic or hydraulic shakers

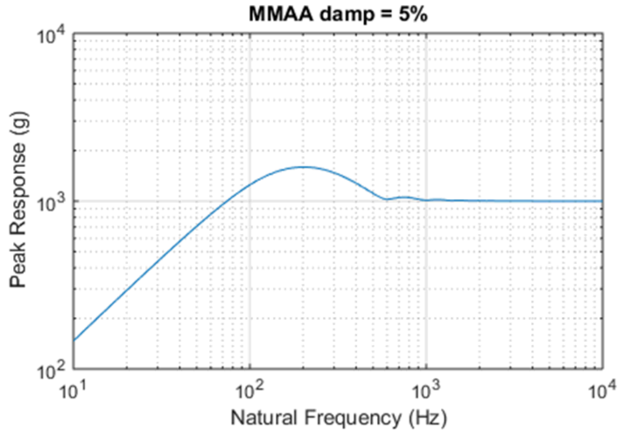
- A problem arises when the field test is not conducted to the full specified levels.
  - Often field tests are performed at lower levels for numerous reasons
    - Safety, cost, limited hardware, etc.
  - Frequently there are few or sometimes only one test data point
    - Hardware and time are often hard to obtain

Drop Table Testing

- Real drop tests are governed by
  - Fall height, Impact surface, and Component structure
- Drop table shocks are defined by
  - Acceleration magnitude, Pulse duration, and Damping coefficient
- Benefits of drop table testing
  - High shock obtained over short durations
  - Lab testing is relatively quick and economical
  - Tests are very repeatable
  - Representative of real-life environments
  - Produces a shock profile that is easily represented mathematically

Typical haversine shock time history and SRS





Energy Scaling – Free Fall

- Assumes that at least one field test has been performed
  - Without any field test there would be no resulting test specification to scale or extrapolate

- Begin with an estimate of the energy in the system
  - For an object in free fall, the energy in the system is easy to define
  - Accelerated fall of a drop table can be related to a free fall event.

- Potential energy: $U_h = mgh$
- Kinetic energy: $T = \frac{1}{2}mv^2$
- Impact velocity: $v = \sqrt{2gh}$

Energy Scaling – Impact Effects

- A higher drop height should result in a greater compression and deformation of the impacting components
- Potential energy stored in a spring is: $U_s = \frac{1}{2}ky^2$
  - y is a combined deflection of components and impact surface
  - Spring rate k is combined component and impact surface stiffness
- Equating initial energy with stored energy gives

$$mgh = \frac{1}{2}ky^2$$

- Solving for y and substituting the natural frequency ω

$$y = \sqrt{\frac{2mgh}{k}} = \sqrt{2gh}\sqrt{\frac{m}{k}} = \frac{\sqrt{2g}}{\omega}\sqrt{h}$$

Impact Depth & Time

- Deflection (impact depth) is given by: $y = y_0 + v_0 t + \frac{1}{2} a t^2$
- Haversine shock velocity change is given by pulse duration and acceleration as:

$$v_0 = \frac{1}{2} a t$$

- Substituting this and $(y_0 = 0)$ gives deflection as:

$$y = a t^2$$

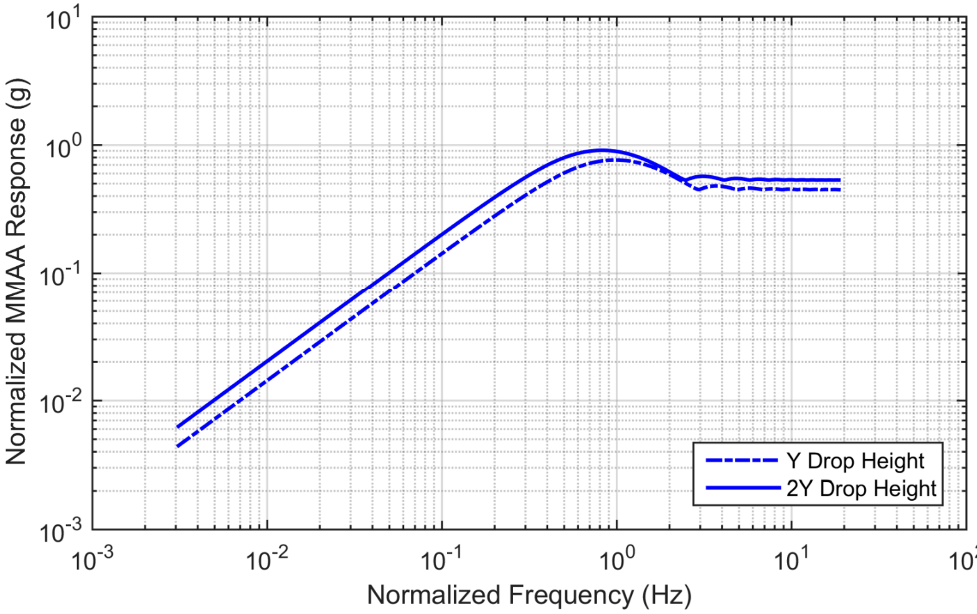
- Therefore:
  - Impact velocity is proportional to the square root of drop height
  - Deflection is proportional to the square root of drop height
  - Impact time is proportional to the square root of deflection
  - Impact time is proportional to the fourth-root of drop height

Haversine Scaling Example

- If the drop height is doubled

$$\Delta h = 2$$
$$\Delta v = \sqrt{\Delta h} = \sqrt{2} \approx 1.41$$
$$\Delta t = \sqrt[4]{\Delta h} = \sqrt[4]{2} \approx 1.19$$

- Resulting Haversine SRS
  - Magnitude increases
  - Frequency decreases



- Ratio between haversines

$$\frac{v_2}{v_1} = \frac{a_2}{a_1}\frac{t_2}{t_1}$$

  - Implies $\Delta a \propto \sqrt[4]{\Delta h}$

Special Case

- Previous derivation holds if the impact surface is unchanged.
- In the laboratory, it is easy to adjust drop table settings and the pulse duration can be held nearly constant
- If pulse durations are not allowed to respond naturally, the previous expression becomes

$$\frac{v_2/v_1}{t_2/t_1} = \frac{\sqrt{\Delta h}}{t_2/t_1} = \frac{a_2}{a_1}$$

- In the special case where $t_1 = t_2$, the acceleration magnitude ratio is equal to the velocity change ratio

Haversine Scaling Relations

- Scale factors used to adjust a haversine shock

$$\frac{v_2}{v_1} = \Delta v = \sqrt{\Delta h}$$

$$\frac{t_2}{t_1} = \Delta t = \sqrt[4]{\Delta h}$$

$$\frac{a_2}{a_1} = \Delta a = \frac{\Delta v}{\Delta t}$$

Shock Test Example

- Recent shock test series provided an opportunity to evaluate the derivation presented here

- Instrumented system tested at three drop heights
  - Although the drop table used here is an accelerated fall table, the carriage accelerometer was integrated to determine impact velocity and the corresponding free-fall drop height.

- Since the previous derivation is always in terms of a ratio, the experimental data is normalized to the lowest level drop test.

Drop Height Ratios

- Drop height ratios between the three tests
  - All data is normalized to shock test #1

Shock Test	Drop Height Ratio, Δh	$\sqrt{\Delta h}$	$\sqrt[4]{\Delta h}$
1	1.000	–	–
2	1.469	1.212	1.101
3	2.482	1.576	1.255

- Pulse duration ratios and the acceleration scale factor
  - Acceleration scale factors needed since pulse duration was altered

Shock Test	Drop Height Ratio, Δh	Pulse Duration Ratio	Acceleration Factor
1	1.000	–	–
2	1.469	0.986	1.228
3	2.482	0.957	1.647

Internal Component Data

- Three internal components were instrumented
  - Component A - 3 gages, Component B – 2 gages, and 1 gage on Component C
- Acceleration and pulse duration were determined by the Nelder-Mead curve fitting algorithm discussed previously
- Components A and B were similar in size and mounting configuration
- Component C was substantially different in size and mounting

Comparison Test 1 to Test 2

- Comparison of test data between shock test 1 and 2
  - All data was normalized to test 1 fixture base levels.
- Behavior of components A and B is similar as expected
- Component C presents a distinctly different response

Component and Location	Shock Test #1		Shock Test #2	
	Normalized Acceleration A_1 (g)	Normalized Pulse Duration t_1 (msec)	Normalized Acceleration A_2 (g)	Normalized Pulse Duration t_2 (msec)
Fixture Base	1.000	1.000	1.3055	0.9863
A-1	0.9678	0.9776	1.1089	1.0682
A-2	0.9202	0.9580	1.1082	1.0442
A-3	0.8522	0.9614	1.0310	1.0493
B-1	0.9121	1.0247	1.0669	1.1055
B-2	0.8493	1.0210	1.0454	1.1133
C	1.8264	0.4690	2.1695	0.4971

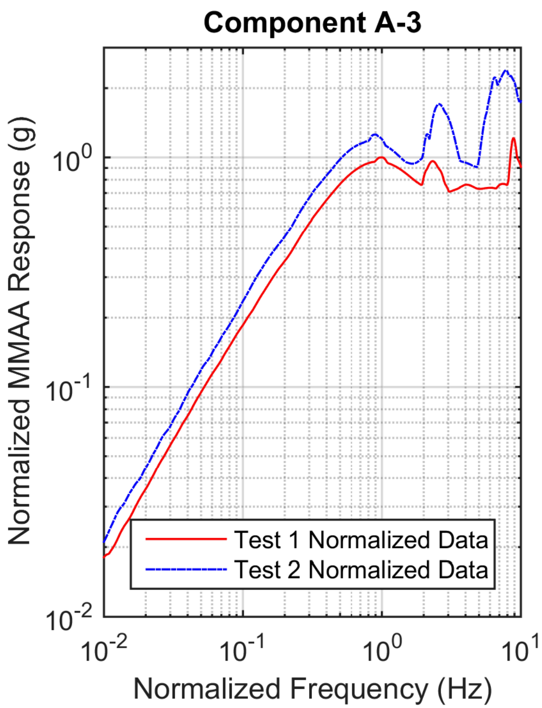
Comparison Test 1 to Test 2

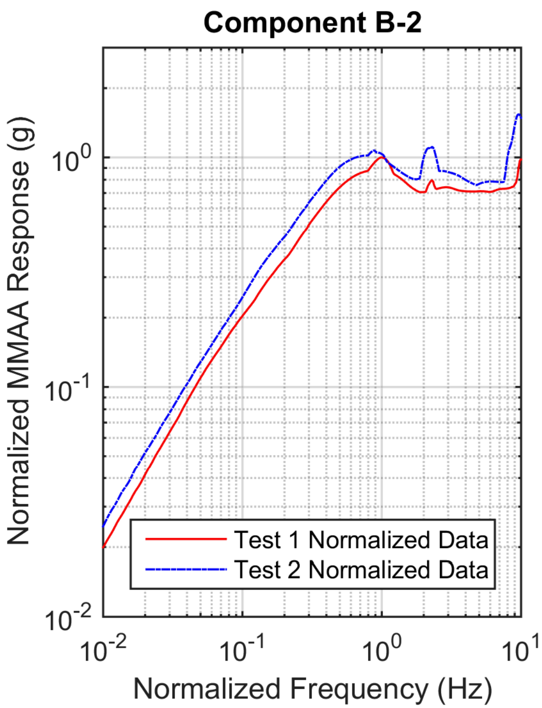
- Calculated acceleration magnitude ratios and pulse duration ratios based on the equations presented previously
- Calculated average ratio compared with theoretical ratio based on drop height comparison
- Results show very good agreement with theory

Component and Location	A_2/A_1	t_2/t_1
A-1	1.1458	1.0927
A-2	1.2043	1.0899
A-3	1.2097	1.0914
B-1	1.1696	1.0789
B-2	1.2309	1.0905
C	1.1878	1.0601
Component Average	**1.191**	**1.084**
Theoretical Value	**1.228**	**1.101**
Percent Error	**3.04%**	**1.54%**

Comparison Test 1 to Test 2

- Test data shown for two gages comparing test 1 and 2
  - Haversine shape clearly moves up in magnitude and shifts down in frequency.





Comparison Test 2 to Test 3

- Half of system base attachment points failed during test 3.
  - Stiffness is significantly altered, do not anticipate match with theory
- Comparison of test data between test 2 and 3
  - Test 2 and 3 data was normalized to test 1 fixture base values
  - Gage on component C failed during test 3 and is not reported here

Component and Location	Shock Test #2		Shock Test #3	
	Normalized Acceleration A_2 (g)	Normalized Pulse Duration t_2 (msec)	Normalized Acceleration A_3 (g)	Normalized Pulse Duration t_3 (msec)
Fixture Base	1.3055	0.9863	1.7117	0.9567
A-1	1.1089	1.0682	1.4389	1.0495
A-2	1.1082	1.0442	1.4378	0.9961
A-3	1.0310	1.0493	1.2998	1.0471
B-1	1.0669	1.1055	1.3572	1.0983
B-2	1.0454	1.1133	1.3809	1.0615

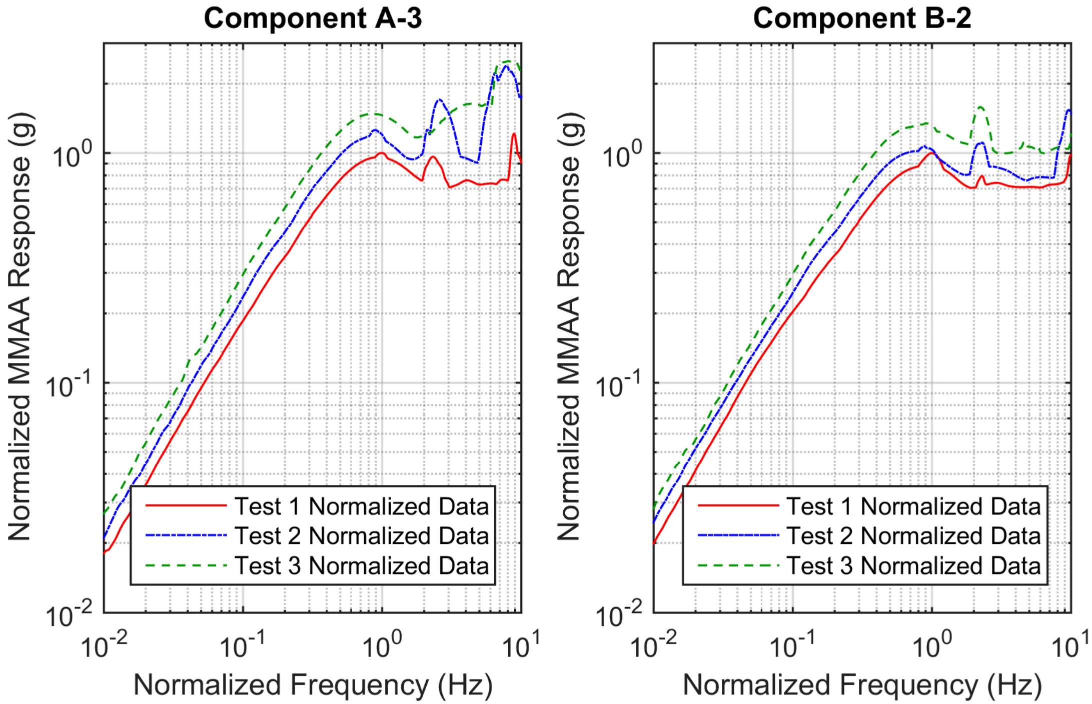
Comparison Test 2 to Test 3

- Acceleration magnitude and pulse duration ratios compared with theoretical ratio based on drop height ratio
- Acceleration magnitude shows very good agreement with theory, pulse durations are significantly off
  - Half of system base attachment points failed during test 3
  - Attachment stiffness was significantly altered during the event

Component and Location	A_3/A_2	t_3/t_2
A-1	1.2976	0.9825
A-2	1.2975	0.9539
A-3	1.2607	0.9979
B-1	1.2721	0.9934
B-2	1.3209	0.9535
Component Average	**1.290**	**0.976**
Theoretical Value	**1.340**	**1.140**
Percent Error	**3.77%**	**14.4%**

Comparison Test 1, 2, & 3

- Test 3 shows the increase in magnitude as expected but no obvious downward shift in frequency
  - Noted that the base attachment points failed during test 3



Conclusion

- Haversine scaling operations should always shift the curve in magnitude and pulse duration
  - Higher amplitude and longer pulse duration
  - Lower amplitude and shorter pulse duration

- Haversine parameters can be extrapolated based on drop height for future tests

- Can also be used to examine existing test data
  - Data that does not follow this scaling pattern is indicative of a fundamental change in the system stiffness