Structural Performance Enhancement with Integral Spring-Damper Elements

~ Four Case Studies ~
Space Shuttle
Atlanta Botanical Gardens Pedestrian Bridge
U.S. Navy
Mk V SEAL Boat
This presentation will introduce you two long-standing axioms in the aerospace/defense community:

1. All shock and vibration is the same . . . it’s only the mass that changes.

2. To mitigate shock and vibration effects on a structure you must:
   - Know the Input
   - Bound the Output
   - Mitigate the Difference
Spring-Damper elements can combine virtually any type of damper or spring combination.

A few examples follow . . .
Mechanical Spring with Fluid Damper
Liquid Spring Dampers
Pneumatic Spring with Fluid Damper and Semi-Active Controls (1965)
Elastomer Spring with Fluid Damper
Mechanical Spring with Friction Damper
(1972)
Case Study #1

Sutong Bridge ~ China

Elastomer Spring plus Fluid Damper
The Sutong Bridge ~ The World’s Largest Cable Stayed Bridge

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Total Length</td>
<td>7.5 km</td>
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<tr>
<td>Tower Height</td>
<td>300 m</td>
</tr>
<tr>
<td>Center Span</td>
<td>1.05 km, 61 m navigation clearance</td>
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<tr>
<td>Expected Ship Traffic</td>
<td>3,000/day</td>
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What the Spring-Dampers Do ~ Axial Direction

- Allow the bridge deck to freely expand/contract with ambient temperature change.
- Protect the 48,000 tonne center span against earthquake and typhoon inputs.
- Reduce motions under synchronized truck/car braking loads – or a massive traffic accident.
Idealized Spring Output Per Unit
Idealized Damping Output Per Unit

\[ F = CV^4 \]

- Extension Displacement:
  - 850 mm
- Compression Displacement:
  - 850 mm
Design Issues

- Gapping required for spring element.
- Peak spring forces roughly 3.3 times higher than peak damping forces.
- Large spring forces limited the choice of spring elements.
  - Mechanical wound coil spring – could not be made.
  - Stacked steel Belleville washers – material fabrication issues, physical size = large.
  - Liquid spring – too large in force to package within damper, cannot be manufactured easily with a tubular cross section.
  - Pneumatic spring – non-linear output, low pressures yielded large package.
  - Elastomer spring – difficult to manufacture. This spring type was selected for the design, using multiple elastomer sections.
Mechanical Design ~ Damper Element
Mechanical Design ~ Add Spring Element

- Threaded Retaining Ring
- Reduced Diameter Region
- Slideable Steel Follower Plates
- Tubular Elastomer Spring Element
Mechanical Design ~ Add Gapping Mechanism

- Extension Pusher Section
- Compression Pusher Section
Compression Engagement of Spring
Extension Engagement of Spring
Assembly and Testing of the Sutong Bridge Spring-Damper

**Proof Pressure Test** – Pressurized internally to 200% of the damping pressure equal to maximum rated damper force. This pressure was held for 3 minutes on each isolator and for 24 hours on the first test article.

**Velocity Testing** – Cycle at various displacements with peak velocities of 50%, 75% and 100% seismic velocity, plus a thermal creep velocity test. End of travel tests performed to verify spring output.

**Wind Fatigue Test** – The first test article subjected to a 50,000 cycle test at plus or minus 5 mm amplitude to simulate wind gusts applied to the bridge structure.
Damper Cartridge Assembly
Sub-Assembly with Spring Elements
Completed Spring-Dampers
Dynamic Testing
100% Speed Damper Sine Wave Tests
Spring-Dampers Installed on Sutong Bridge
Case Study #2

Space Shuttle Mobile Launch Platform (MLP)
Mobile Launch Platform (MLP)
Inside the MLP

Mobile Launch Platform No. 1
Dynamic Environment

- Defined by direct measurement:
  - Floor response of the MLP during launch was captured using accelerometers in the vertical direction during a recent Shuttle mission.
  - This response was then converted into the form of a Power Spectral Density, PSD.
  - This data was to be used as the input to which the system was to be analyzed.
Switchgear Analytical Response

Switchgear Response at Center of Gravity: Z-Direction

PSD (g²/Hz)

Frequency (Hz)
Spring-Damper Assembly
STS-115 Shuttle Launch ~ September 9, 2006
Field Verification Video
STS-117 Shuttle Launch ~ June 8, 2007
Z-Direction

STS-117 Launch Maximum G-Force in Z-direction

Change in G Force Percentage

<table>
<thead>
<tr>
<th></th>
<th>Maximum</th>
<th>Minimum</th>
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<tbody>
<tr>
<td>Z</td>
<td>71.32%</td>
<td>70.35%</td>
</tr>
<tr>
<td>Z</td>
<td>73.44%</td>
<td>77.17%</td>
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Case Study #3

S-Shaped Pedestrian Bridge at the Atlanta Botanical Gardens
Atlanta Botanical Garden ~ Twisting Turning Bridge
Atlanta Botanical Garden ~ Cantilevered Mast Supports
The Inputs

- Pedestrian induced vibration
- Possible synchronous footfalls
- Wind
- Hurricanes
Atlanta Botanical Garden ~
Supporting Mast with Damper and Spring
Problems:

- Near-zero hysteresis for occupant comfort
- Extremely long life; spring-dampers must continuously cycle
- Relatively low-cost, no time for research

The solution already was built – and slated to be installed in space at the International Space Station
CTC Spring-Dampers
CTC-3 in Shuttle Payload Bay
CTC-3 Installed at ISS
Zero Hysteresis Damper
Machined Spring Element
Atlanta Botanical Spring-Damper
Atlanta Botanical Garden
Atlanta Botanical Garden
Atlanta Botanical Garden
Case Study #4

Passive Spring-Damper Elements to Reduce Occupant Shock in the U.S. Navy’s Mk V SOC Seal Delivery Boats
Mk V SOC

Length = 25 m
Power = 5,000 hp from twin diesel engines
Speed = 80+ km/hr
The Problem

- Accumulated stress on occupants from continuous high speed boat operation in the open ocean – 1-3 G typical at 2 second period for 10-12 hour missions.
- Shock related injuries from rogue waves.
- Hospitalization rates for Mk V personnel 5.6 times that of average naval personnel. Typical injuries were to neck and spinal column.
- Occupant and gear weights varied dramatically.
- Ideal element for continuous operation was a pure spring having damping in the 20% range and a relatively soft spring rate.
- Ideal element for rogue waves was a stiff, heavily damped spring with time-wise variable damping necessary for proper pre-positioning of the occupant’s head and neck.
64% of all crew members on all boats reported at least one and up to three injuries.

Injuries included:
- Sprains
- Dislocated spinal discs
- Trauma
- Dislocated joints
- Stress fractures
- Continuous pain
Reduce the Dynamic Response Index

$$DRI = \left( \omega_n^2 |x_s - x_l| \right) / g$$

$$X_s = \text{Base Motion} \quad X_l = \text{Seat Cushion Deformation}$$

Reduce the equivalent cumulative static compressive stress ($S_e$) defined in DRAFT ISO/DIS 2631-5

$$S_e = \left[ \sum (m \cdot D)^6 \right]^{1/6} \quad \text{MPa}$$

$$m = \text{Stress Factor}$$

$$D = \text{Acceleration, M}/\text{Sec}^2$$
Optimization Parameters

- DRI indicative of worst case event, regardless of time.

- Se is the result of a weighting process of all peak acceleration values projecting a short duration event to a more extensive time frame. Quantifies cumulative injury.
First mode, human torso \( \approx 8.4 \text{ Hz} \)

Damping factor measured for torso = \( .22 \ C_{CR} \)

Initial studies used a human body model from the U.S Army, developed to study helicopter crash results

Subsequent studies moved up to a GEBOD human body model from the auto industry – 77,000 DOF
May 1649: Deck Heave (Input)
Accel. (g's) vs. Time
Analytical Results

- A velocity dependent (adaptive) damping coefficient was able to give a soft ride at low sea states yet offer high capacity in severe seas.

- Directional dependent damping provides high energy capacity in the compression direction, while allowing quick return to the extended position in time for the next event.

- Multi-linear spring rate offers extra energy capacity.

- Weight variability of riders predicted to have minimal effect on Se and DRI.
Resulting Isolator Attributes

- 175 mm of normal stroke followed by a non-linear elastomeric snubber
- Bi-directional damping function
- Adaptive design with velocity sensing valves
- Quadri-linear spring rate
- Adjustable spring preload
Four isolators designed and manufactured to bracket the targeted solution:

<table>
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<tr>
<th>Isolator</th>
<th>Description</th>
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<tr>
<td>ALPHA</td>
<td>Analytically optimized isolator</td>
</tr>
<tr>
<td>BRAVO</td>
<td>Stiffer isolator with higher total energy capacity</td>
</tr>
<tr>
<td>CHARLIE</td>
<td>Similar to ALPHA, but faster reacting valving to produce slightly higher energy capacity</td>
</tr>
<tr>
<td>DELTA</td>
<td>Softer isolator, altered valving</td>
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Mk V SOC
Suspension Seat
Sea Trial Tests

- Mk V SOC #973 outfitted with one of each isolator in the front four seats
- Mk V SOC #974 followed with rigid seats
  - NSWG4, SBT 20, DET 3, January 2003
  - 650 mile transit between Little Creek, VA and King’s Bay, GA
  - One planned refueling stop in Cape Fear, NC
  - Encountered 4-6 foot seas; 8 foot seas on return
- Additional tests were run in Atlantic and Pacific
“The new seats are a great success. It’s allowed the crew to push the boat faster than the boat can actually handle.”

“At first, we instinctively braced for the impacts, but as we got used to the seats, we relaxed and let the shock absorbers do their job.”

“When we pulled into Cape Fear on the first night, the crew of 973 was still fresh. We could have refueled and then completed the transit without an overnight stay.”
“We encountered eight foot seas and had to slow to (xx) knots because the crew of 974 (without isolated seats) were getting pounded. The crew of 973 had no problem at (xx) knots.”

“During these long transits we will save significant time while preventing crew injury and fatigue with the new seats.”

“These seats will both spare SWCC (Special Warfare Combatant Crewmen) from many injuries, and expand our tactical performance by allowing us to operate faster for longer periods of time.”

“Seats handled beautifully. There was a noticeable difference between riding in the shock seats during high seas versus riding in the non-shock mounted seats.”
“They ride like a Caddy!”

- Preferred isolators: ALPHA and CHARLIE
- BRAVO: Too stiff
- DELTA: Too soft (occasionally bottomed)

All Mk V SOC have now been back-fitted with the new seats incorporating Spring-Damper elements.
Spring-dampers can combine dissimilar spring and damping elements.

Optimization of any specific design is driven by:

- Absolute values of spring force and damping force
- Available package envelope
- Material available for spring elements
- Required suite of output requirements
Conclusions – The Two Axioms

1. All shock and vibration is the same . . . it’s only the mass that changes.

2. To mitigate shock and vibration effects on a structure you must:
   - Know the Input
   - Bound the Output
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You make the call!
Acknowledgements

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