Rapid Machine Design

Eberhard Bamberg[1], Alexander H. Slocum[2]
Massachusetts Institute of Technology, Cambridge MA

The methodology of rapid machine design attempts to shorten design-to-manufacture time of production equipment by using advanced engineering tools such as Computer Aided Design systems (CAD) and Finite Element Analysis (FEA) during the conceptual design phase. It is hypothesized that by identifying the best of all available design concepts, overall development time can be shortened. Further time savings result from building machine components out of fabricated structures instead of casts. This eliminates the need for making molds and other specialized tooling systems, and provides a high degree of flexibility in terms of changing the design and/or making modifications to design specifications.

Fabricated Structures

Traditionally, the base and other major components of a machine tool have been made of gray or nodular cast iron, which has the advantages of low cost and good damping, but the disadvantage of heavy weight. Casting is a net-shaping process whereby molten metal is poured into a mold, thereby assuming its shape upon solidification. In modern equipment design, lightweight structures are desirable because of ease of transportation, higher natural frequencies, and lower inertial forces of moving members [Kalpakjian]. Lightweight designs are a basic goal in rapid machine design and require fabrication processes such as mechanical fastening (bolts and nuts) of individual components and welding. A fabricated design consists of pre-cut stock materials such as plates, tubes, channels, and angles which are joined together to form the structure. Such stock items are available in a wide range of sizes and shapes and have some highly desirable mechanical properties such as formability, machinability and weldability. Of special interest are round and rectangular tubes whose closed cross sections have a very high stiffness-to-weight ratio.

In rapid machine design, fabrication is the preferred technique because of the following key advantages:

- Low fixed costs make it highly suitable for low to medium production volume.
- Fabrication can easily be done in-house, making the need for outsourcing obsolete.
- Use of highly standardized materials ensures high availability and competitive prices.
- Fabrication equipment is rather inexpenssive.
- Minimum tooling costs. Fabricated structures only need some form of fixturing which is universally applicable. No expensive molds are required.

---

[1] Research Engineer, Department of Mechanical Engineering, MIT Room 3-470, Cambridge, MA 02139

[2] Professor of Mechanical Engineering, MIT Room 4-445, 77 Mass Ave., Cambridge, MA 02139

- Minimum lead time. No proprietary tooling such as molds are required, shortening design-to-manufacture time.
- Great scalability. No re-tooling required when scaling the design to change available workvolume.
- High flexibility. Design changes are not impaired by existing tooling, making alterations inexpensive and easy to implement.
- Modular components can initially be fabricated separately and then joined whenever it is convenient.

However, fabricated structures have also a few disadvantages associated. These include:

- Comparably high variable costs prohibit large production volumes.
- Structures generally need stress-relief either through thermal or vibrational relaxation.
- All welds should be reasonably accessible, imposing sometimes hard to meet design constraints.
- Fabricated structures have much less damping compared to cast-iron based designs, requiring other forms of damping such as constrained layer damping.

Despite the shortcomings listed above, designing and building a machine as a fabricated structure has the big advantage of a much lighter design with a substantially shorter lead-time compared to a cast design. This is especially true for the case where the base is built from round tubes as opposed to flat plates, because round structures offer better strength-to-weight ratios and are more readily available.

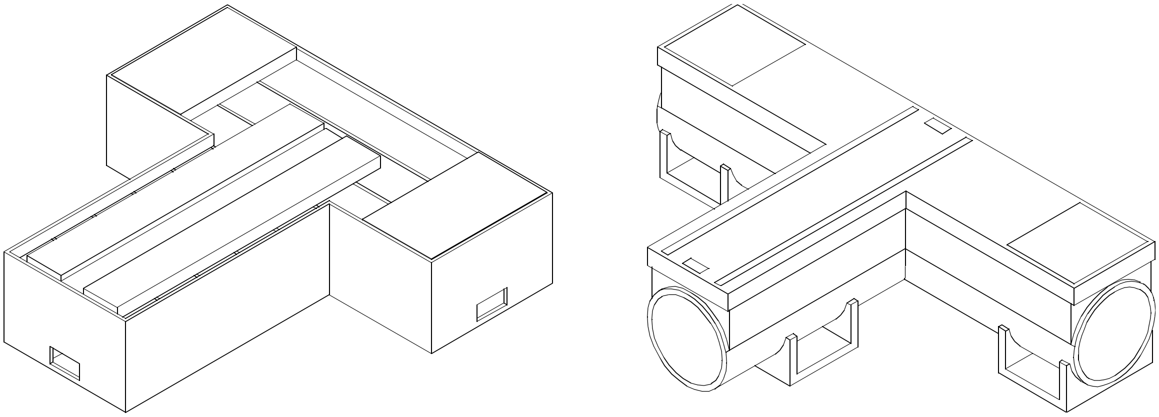

FIGURE 1. Conventional base built from plates vs. base built from round tubes

Constrained Layer Damping

Welded machine tool structures provide easy scalability in terms of size and outstanding flexibility in terms of fast design and fabrication; however, damping of the structure is a very critical issue. Unlike cast iron or polymer concrete-based components, welded steel plates have virtually no internal damping and are therefore prone to unwanted vibrations. Filling the structure with concrete or sand adds damping but also a great deal of unwanted weight. A better approach is the use of constrained layer damping where a viscoelastic layer is squeezed between the structure and one or more constraining layers. Kinetic energy from relative motion between the structure and the constraining layer as it occurs during bending or twisting gets dissipated into heat by the viscoelastic layer. This mechanism introduces damping into the system, thereby limiting the structure's response to excitation frequencies near its modes. Unfortunately, existing shear layer damping designs tend to be costly to implement.

For machine structures, internal damping designs are most appropriate because they allow to maximize the structural cross sections, resulting in excellent strength-to-weight ratios. For tubular structures, constrained layer damping can be reasonably easy achieved with the ShearDamper™[1] design (Figure 2). Here, the constraining layers are created by cutting 8 slots starting from both ends of the tube until the cuts almost meet in the center of the tube. Next, a sheet of damping material (ISODAMP™ C-1002[2]) with adhesive on one side is wrapped around the split tube and the entire assembly inserted into the tubular machine structure. As the next step, the ends are sealed off with silicon and the gap between the damping layer and the outer structure is being filled with either epoxy or VibraDamp™[3], a lower-cost alternative to epoxy which is essentially epoxy resin heavily filled with inert material.

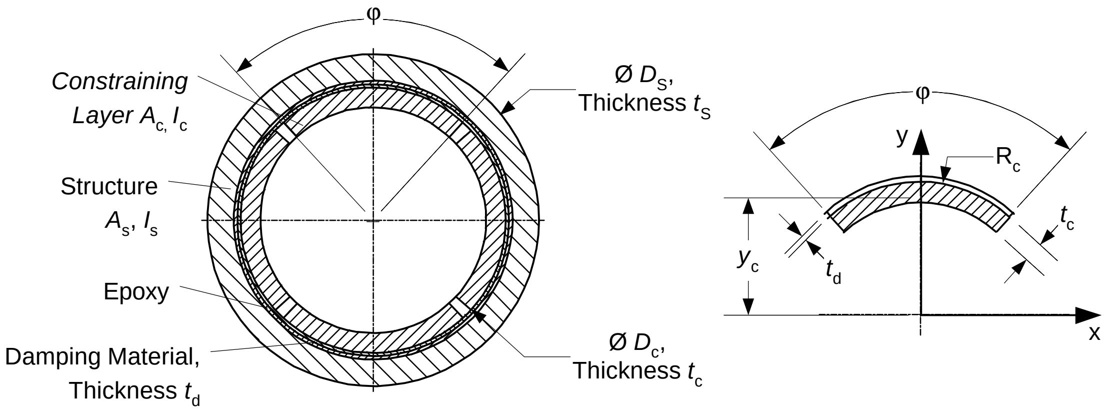

FIGURE 2. ShearDamper™ design parameters

While the ShearDamper design offers good performance, due to its complex design it also adds significantly to the cost of the structure. Next, alternative designs are presented with the following idea: replace the split tube with less expensive structural materials and possibly increase the damping performance even further. Concrete, for instance, is very inexpensive and has a respectable amount of damping built-in. This new design would make use of “sausage-like” damping sheet enclosures which are inserted into the structural tube. The bottom ends are closed off and the center of this assembly is supported by a thin-walled tube. Finally, the four sausages are evenly filled with concrete with an expanding agent added. The added grout agent, which contains aluminum powder, oxidizes during the curing of the concrete,

---

[1] ShearDamper™ is registered trademark of AESOP Inc.

[2] ISODAMP is a trademark licensed to AERO company

[3] VibraDamp is a registered trademark of Philadelphia Resins

thereby producing little hydrogen bubbles. The gas causes the concrete to expand and counteracts its tendency to shrink during the curing. In fact, when dosed properly, the volume actually increases a bit, causing the damping material to be pressed against the inner diameter of the structural tube as well as against the outer diameter of the central supporting tube. The pressure exerted will be large enough to create enough friction to keep the damping sheet from sliding along those two surfaces. If this wasn't the case, damping performance would not be as good as anticipated. The inner support tube can either be a round or a square tube and, provided that its stiffness is properly tuned to that of the concrete constraining layer, can add a significant amount of extra damping. Once the concrete is cured, the ends are cut off and the concrete is sealed with a layer of coating that prevents moisture from entering the system.

The new constrained layer damping design offers significantly improved damping performance at only a fraction of the cost of a conventional system. The improvement can be seen in Figure 3. The sand- and concrete filled designs as well as the ShearDamper design exhibit vibration in excess of 8 ms, while the novel concrete designs have no measurable vibration after 3 and 2 ms, respectively.

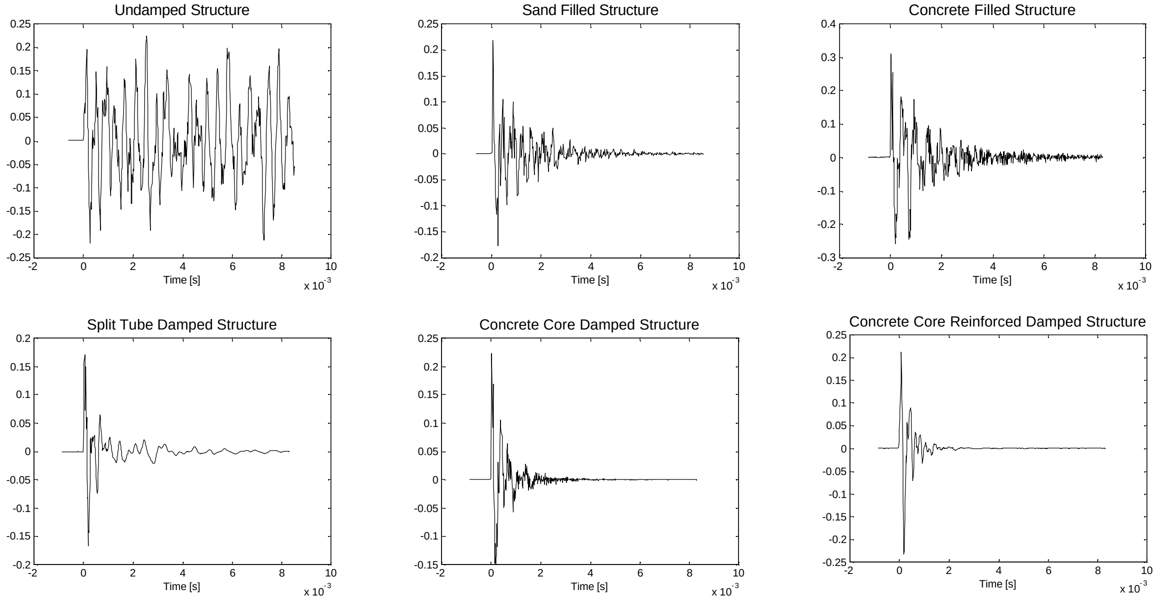

FIGURE 3. Time response for various damping designs

References

Kalpakjian, S., *Manufacturing Engineering and Technology*, Addison Wesley, p. 611, 1995.

Slocum, A.H., Marsh, E.R., Smith, D.H., New Daper Design for Machine Tool Structures: the Replicated Internal Viscous Damper, Precision Engineering Journal of the American Society for Precision Engineering, Vol. 16, July, pp. 174-183, 1994.

Marsh, E.R., Slocum, A.H., *Integrated Approach to Structural Damping*, Precision Engineering Journal of the American Society for Precision Engineering, Vol. 18, Apr-May, pp. 103-109, 1996.