EDITORIAL

First Principles

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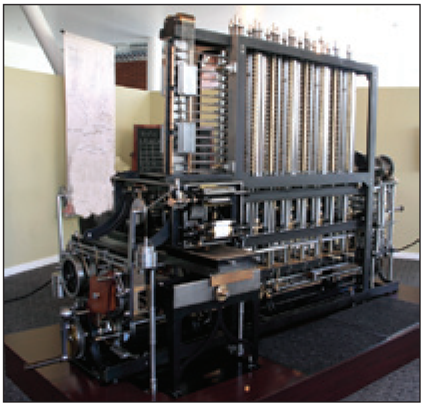
In the lobby of the Computer History Museum in Mountain View, CA, there is an amazing machine called The Babbage Difference Engine No. 2, which is one of the first mechanical computers ever designed. (http://www.computerhistory.org/babbage/)

It was designed by Charles Babbage in 1849, but sadly his engine would not be built in his lifetime, and his design would sit idle for more than 150 years. But in 2002 a London team of dedicated engineers and technicians built this engine, faithfully adhering to Babbage's drawings. To everyone's astonishment, it worked exactly as Babbage had intended! Keep in mind that the engine consists of 8,000 parts, weighs 5 tons and measures eleven feet long and 7 feet high. The engine that is in the museum in Mountain View is an exact replica. I have seen it run, and it is truly amazing.

Even more amazing to me than its actual operation is that it worked as Babbage had intended on the first try. Every gear, every lever, every shaft, every bearing had to be designed perfectly, with no errors or oversights and with proper accommodation of manufacturing tolerances for the machine to turn and generate accurate results. This is astounding as seen from the viewpoint of our 21st-century approach to engineering such complex systems. We just don't do things that way anymore.

If we were given the task of creating this machine today, we would no doubt follow a process something like this:

- Benchmark other mechanical computers and establish system-level targets.
- Cascade these targets down to the component level.
- Develop a basic concept.
- Build simulation models from this concept and iterate until the simulation results gave confidence that the machine would work.
- Create proof-of-concept prototypes or scale models, and conduct performance testing to ensure functionality as intended.
- Develop a detailed design.
- Build a rough representative prototype of the full machine based on the detailed design.
- Conduct extensive testing on this prototype and assess against targets, identifying any problems and developing potential solutions.
- Iterate on the detailed design based on lessons learned from above testing and then re-test to validate design changes, assessing against targets along the way.
- Finalize the design.
- Build a complete as-designed "working" machine and conduct validation testing to ensure all targets are met.



- Fine tune the design based on lessons learned from this round of testing.
- And finally . . . build a fully functional machine and enjoy.

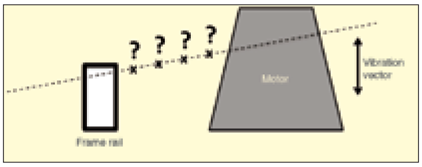
This is not unlike how we design and engineer cars today. But Babbage didn't do that. He took out his drafting tools and simply designed it right the first time – all 5 tons and 8000 parts of it. How in the world did he do that? Furthermore, why can't we today simply design our complex machines correctly right out of our heads on the first try?

Well, let's first acknowledge that Babbage was most likely an extremely intelligent man, perhaps even a genius, so perhaps he had a leg up on the rest of us. That said, Babbage certainly had an incredibly deep understanding of mathematics, physics and mechanics (such that they knew in the mid 19th century), and he had been spending years making more and more complex machines by the time he designed Difference Engine No. 2. In fact, he had built a small working prototype of a small section of the predecessor to Differential Engine No. 2, which of course, worked as intended.

So it seems that Babbage was incredibly bright, had years of experience and applied "first principles" to his design, and this is how he managed to design such a complex system right the first time. Can we engineer complex machines this way today? To a degree, I believe we can.

Here's a simple example of how first principles can directly lead to a design. In developing the motor mounting system for an automobile, the engineers need to decide where in space to locate one of the motor mounts (among others). Based on some previous calculations, the engineers know that the motor mount should be placed anywhere along a lateral axis of the car. This axis, in fact, is the torque roll axis of the motor about which it rotates under torque. This means that this particular motor mount doesn't need to react to torque loads from the motor, and only needs to support the weight of the motor (and provide vibration isolation).

The figure below shows the basic situation.



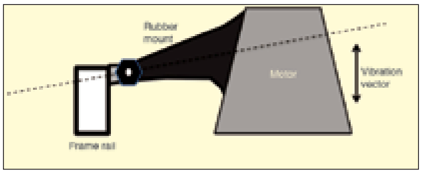
So the question is, where along the axis should they place the motor mount? Applying first principles will take them a long way toward answering that.

First Principle No. 1 – For rubber isolators to work effectively, the attaching structure on either side of the rubber mount must have much higher stiffness (both static and dynamic) than the stiffness of the rubber itself.

First Principle No. 2 – The static (and dynamic) stiffness of a cantilevered beam is inversely proportional to the cube of the beam length.

First Principle No. 3 – The torsional stiffness of a beam section is proportional to the 4th power of the radius (for a circular section).

By applying these first principles and a little experience to the design problem shown, the answer to this question is quite straightforward: Locate the mount closer to the body frame rail and farther from the motor, as shown below.



Here's why – Experience tells us that body brackets tend to be made from welded stampings, while powertrain brackets tend to be metal castings. In general, castings provide higher bending rigidity than stampings. Also, the casing of the motor is much larger than the body rail and is most likely a thick-walled casting, and so it is much stiffer than the box-beam section of the frame rail. For these reasons, a cast motor mount bracket and the cast structure of the motor itself provide a stronger support to react the moment generated by the force-distance of the motor mount. Also, the shorter stamped bracket to the rail minimizes both the L-cubed effect of the beam as well as minimizing the torque applied to the frame rail, which is inherently less stiff in torsion than the motor block. For these reasons, the engineers concluded, based on first principles alone, that the mount should be located farther from the motor and closer to the frame rail.

The exact location will most likely be determined by packaging space and manufacturability constraints, so additional complex analysis to perfectly locate the mount may not even be needed. The right answer may simply be: "As close to the rail as you can get it, as long as it stays on the torque axis."

The more common (and accepted) approach to solve this problem is to benchmark the competition to establish targets, then build a model of the motor, the mounting system, and the body structure and run a series of what-if studies to see which location yields the best result to achieve the desired target. More advanced optimization routines can also be applied to the model to locate the exact position of the motor mount.

Don't get me wrong – this method works really well and almost always yields a good result. I have been a huge proponent of benchmarking and CAE-led design most of my career. The big problem with it is that it takes a lot of time, money and manpower. In my recent experiences at an electric-vehicle startup, where time, money and manpower were in scarce supply at the early design stages of the vehicle, first-principle-based decision making was the only way to move forward and design the car. The engineering team made a lot of early decisions this way, with little (but some) analysis and no hardware testing, since there was no hardware available to test. This is what allowed them to create a truly groundbreaking vehicle from a clean sheet to the start of production in three years. They key to the success of this program was the initial first-principle-based design philosophy.

I would also add that it was a lot of fun! It was both liberating and a little frightening to make really significant mechanical decisions with which you knew would live for the life of the vehicle based on some whiteboard scribbles, hand calculations and your best understanding of physics. At the very least, it forced me to think much harder about the physics of a particular problem and showed me how much can be achieved just by using your brain and applying first principles. I think Mr. Babbage would have approved. SV

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