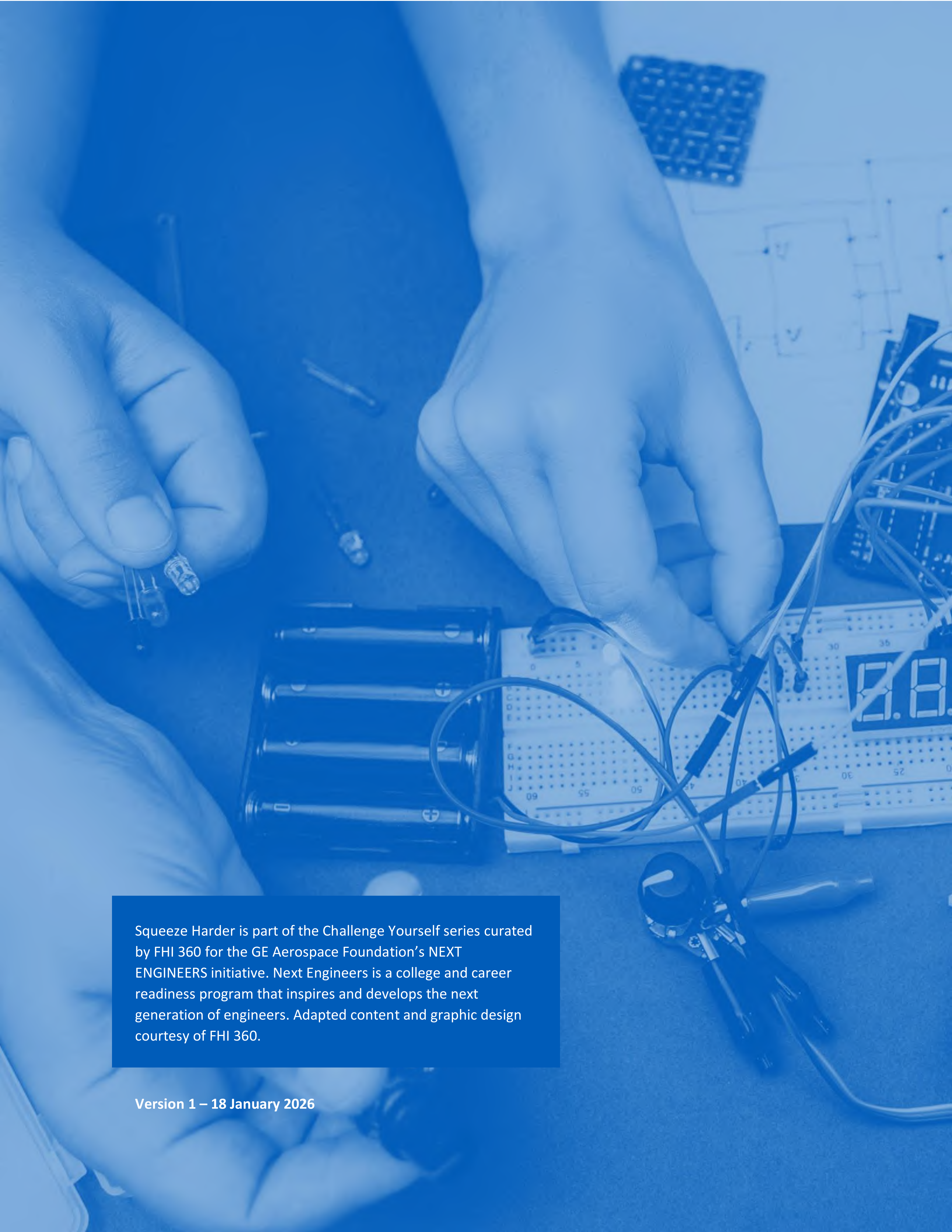
NEXT ENGINEERS

CHALLENGE YOURSELF

Extreme Machine Part 3: Squeeze Harder

Aeronautical Engineering

NEXT ENGINEERS



Squeeze Harder is part of the Challenge Yourself series curated by FHI 360 for the GE Aerospace Foundation’s NEXT ENGINEERS initiative. Next Engineers is a college and career readiness program that inspires and develops the next generation of engineers. Adapted content and graphic design courtesy of FHI 360.

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Extreme Machine Part 3: How to Squeeze Harder

NERD OUT

What is Compression Ratio?

As we saw in part 1 of this series, the air entering the core of a jet engine does not go straight to the combustion chamber. Instead, it is first highly compressed. Compression is one of the most powerful ways engineers have to improve jet engine efficiency.

Compressing the air as much as possible does three important things:

1. It **improves combustion efficiency**: Dense, compressed air allows fuel to burn more completely. There is more oxygen contained in a smaller volume.
2. It **increases thermal efficiency**: According to thermodynamics, higher compression lets the engine extract more useful work from the same fuel. This is called thermal efficiency.
3. It **reduces fuel consumption**: More energy is converted into thrust instead of wasted as heat.

In simple terms, better squeezing, leads to better burning, which results in better efficiency.

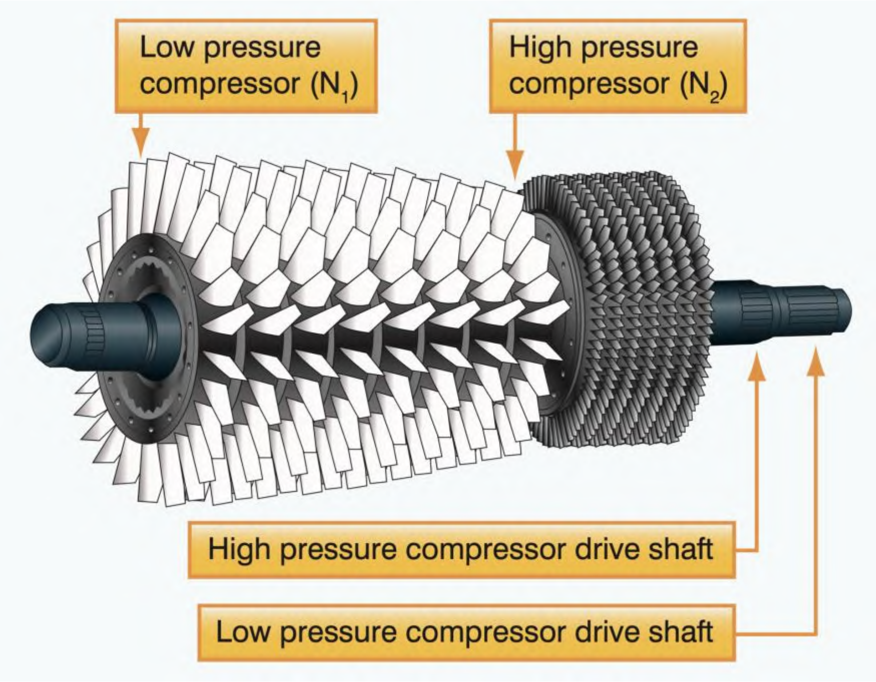


Diagram of a 2-stage compressor
Image by Federal Aviation Administration is in the public domain
https://commons.wikimedia.org/wiki/File:Dual-spool_axial-flow_compressor.png

THERMAL EFFICIENCY

Thermal efficiency is a measure of how effectively the engine converts the chemical energy in the fuel into useful mechanical work (thrust). It is typically expressed as a percentage of fuel energy not wasted as heat.

Thermal efficiency is given by

$$\eta = \frac{1}{(P_{out}/P_{in})^{(\gamma-1)/\gamma}}$$

where
P_{out} and P_{in} are the pressure of the air exiting and entering the compressor respectively.

All you need to see is that the greater this ratio (or the greater P_{out} is, the greater the overall efficiency.

The amount of “squeeze” provided by the compressor is called the **pressure ratio (PR)**. It is simply the ratio of the air pressure leaving the compressor to the air pressure entering it or

$$PR = \frac{P_{out}}{P_{in}} = P_{out}:P_{in}$$

A PR of 20:1 means the air pressure is increased 20 times (it is 20 times greater when exiting the compressor than when entering). Modern GE engines exceed 25:1 – levels that would have seemed impossible decades ago.

OVERALL COMPRESSION RATIO

If you also consider the increase in pressure provided by the huge fan in modern turbojet engines, the overall increase in pressure between the air entering the engine and that entering the combustion chamber is even greater. This is called the **overall compression ratio (OCR)**. The GE9X boasts an OCR of 60:1 with a compressor PR of 27:1.

How Jet Engines Compress Air

Compression happens in stages, not all at once. Trying to compress all the air at once would stall the flow and shut the engine down. A compressor consists of a series of rotating blades (rotors) alternating with stationary vanes (stators). Each pair of rotors and stators adds a small pressure increase. Together, dozens of these stages multiply the pressure dramatically.

A modern turbofan has 2 distinct compressor sections:

- The **low-pressure compressor** (LPC): This is immediately after the fan and has fewer stages (normally about 3 - 6) and larger diameter blades. It provides a moderate pressure increase (2:1 to 4:1) at low speeds (between 3,000 and 5,000 RPM). Its main job is to precondition the air to increase the efficiency of the high-pressure compressor.
- The **high-pressure compressor** (HPC): This has more stages (normally about 8 - 14) and smaller diameter blades. It spins faster (between 10,000 and 15,000 RPM) and can achieve PRs of 15:1 to 25:1.

This design lets the LPC spin slower (at a similar speed to the fan) while the HPC spins faster for peak efficiency, enabling overall PRs of 40:1 to 50:1.

Take a closer look at a real life jet engine compressor in action in the video called Compressors - Turbine Engines: A Closer Look (7:47): (https://www.youtube.com/watch?v=CXSi4GXUojo).

FASTER THAN SOUND

The tips of the high-pressure compressor blades in many GE engines travel faster than sound. For example, the blade tips in the GE90 compressor travel at between **Mach 1.2** and **Mach 1.6**. The speed of sound is **Mach 1**.

Adding More Squeeze

Increasing the PR sounds simple – just add more stages and make the blades spin faster. However, as we have come to expect, this is no free lunch. Each increase introduces new problems.

- **Heat builds up quickly**: Compressing air raises its temperature. At very high compression, air exiting the compressor is extremely hot and places the materials under enormous thermal stress. Too much heat reduces component life and reliability. Therefore, component cooling becomes essential.
- **Aerodynamic stability decreases**: When air gets highly compressed, it is more prone to flow separation, compressor stall, and surge (a violent reversal of airflow). Preventing this requires very precisely shaped rotor blades, stator vanes that can be adjusted and advanced control systems to make these adjustments. This all adds cost and complexity to the design.
- **Mechanical loads increase**: Higher compression needs faster spinning blades which, as we saw in part 2, greatly increases the centripetal forces (remember

that $F = m\omega^2 r$). Therefore, the compressor blades experience huge forces trying to tear them apart every second the engine runs. This requires making blades that are light, strong, and fatigue-resistant - a major materials engineering challenge.

- **Manufacturing precision matters more**: To more effectively achieve high compression ratios, the gaps between rotor blades and stator vanes must be as small as possible. All the components must also be perfectly and uniformly shaped. Tolerances need to be measured in fractions of a millimeter and advanced manufacturing and quality control are essential but time consuming and expensive.

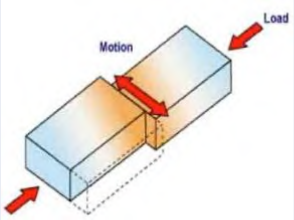
But engineers don't maximize compression blindly. At some point, adding more stages adds too much weight, more intricate blade designs with tighter tolerances raise costs and complexity, and higher temperatures reduce component durability. Therefore, the best design is not actually the highest PR design - it's the optimum PR design.

Some Ingenious Solutions

GE engineers have developed many ingenious ways of producing compressor blades able to withstand the enormous pressures, high temperatures, and punishing mechanical stresses that come with ever greater PRs.

Instead of making the rotors as a central hub with many attached blades, rotors are made as **blisks**. "Blisk" is a portmanteau of blade and disk and is a rotor disk and blade machined out of a single piece of material.

A compressor blisk
Image by Olivier Cleynen is released under a CC-BY-SA licence
https://en.wikipedia.org/wiki/File:Compressor_blisk_on_display_(2).jpg



LINEAR FRICTION WELDING

One of the clear downsides of blisks is that if one blade gets damaged it can be hard to just replace that one blade. But **linear friction welding** makes this possible.

This is a technique of fusing 2 pieces of metal by pushing them together very firmly and then vibrating one of the pieces to create friction and heat. This causes the pieces to fuse without melting and avoids the defects that melting produces.

Watch a weld

The benefits of blisks include weight savings (there is no need for blade attachments), improved aerodynamics (there are no gaps between the blades and the hub), and better reliability (there is far less chance of a blade detaching). But there is a trade-off. If one blade is damaged, the entire blisk may need to be replaced.

To see how a blisk is machined out of a single piece of titanium watch the video called Blisk Manufacturing (1:44) (https://www.youtube.com/watch?v=FCfZQMPQa7g).

Secondly, engines like the GEnx, have compressor blades of titanium aluminide (TiAl). TiAl has several advantages over traditional titanium alloys. It is lighter (4 g/cm^3 vs 4.5 g/cm^3), more heat-resistant (up to 800°C vs about 550°C), stiffer and reacts less with oxygen and nitrogen at high temperatures, meaning that the compressor can run faster for improved PRs.

However, titanium aluminides are more brittle than traditional titanium alloys and need more complex and expensive manufacturing techniques.

Read The Evolution of Compressor Blades: From Steel to Titanium to Ceramic Composites (https://safefly.aero/the-evolution-of-compressor-blades/) to learn more.

Engineering Trade-offs

As we have seen increasing the PR in a jet engine improves fuel efficiency and boosts overall engine performance. But this comes at the expense of increased heat, mechanical stress, and expensive manufacturing and operational complexity. Each extra unit of compression delivers diminishing returns. An engine that is slightly less efficient but significantly more durable can still save airlines millions of dollars over its lifetime.

In the next article, we'll move to the hottest part of the engine where engineers push combustion temperatures far beyond what materials should be able to tolerate but find ways to make them survive anyway.

TITANIUM ALUMINIDES

Titanium aluminides are classified as ordered intermetallic compounds, which means they form when atoms of two or more metals (in this case titanium and aluminium) combine in a fixed ratio to produce a crystalline material with a different structure than either of the individual metals.

Dive deeper