

# THE DEPARTMENT MAGAZINE

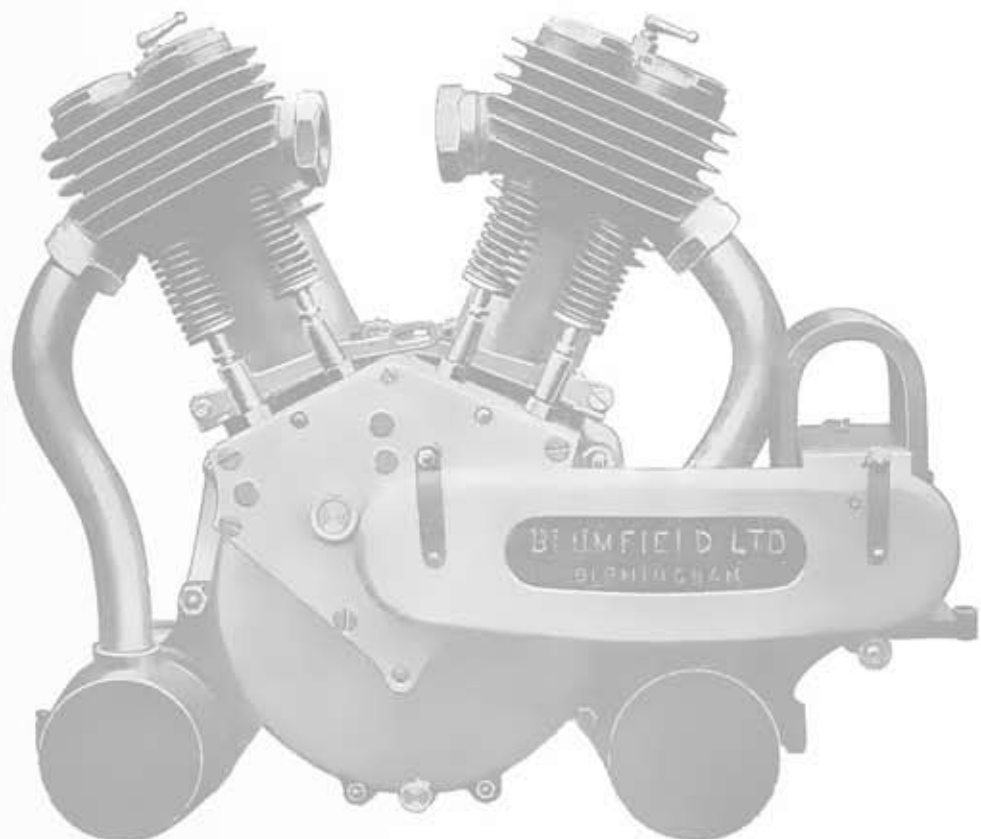
Department of Mechanical Engineering

# MECH ZINE

**VOLUME 2** **ISSUE 2**

The Gear of Tomorrow

If its broken,  
take it apart  
and fix it.



ACADEMIC YEAR 2015 - 2016

## **KSR INSTITUTE FOR ENGINEERING AND TECHNOLOGY**

### **Vision**

To become a globally recognized Institution in Engineering Education, Research and Entrepreneurship.

### **Mission**

<b>IM1</b>	Accomplish quality education through improved teaching learning process
<b>IM2</b>	Enrich technical skills with state of the art laboratories and facilities
<b>IM3</b>	Enhance research and entrepreneurship activities to meet the industrial and societal needs

## **DEPARTMENT OF MECHANICAL ENGINEERING**

### **Vision**

To produce globally recognized Mechanical Engineers and Entrepreneurs to meet the industrial challenges with ethical values.

### **Mission**

<b>DM1</b>	Impart quality education in Mechanical Engineering through enhanced teaching learning process.
<b>DM2</b>	Provide platform to apply and analyze the engineering concepts with state of the art laboratories.
<b>DM3</b>	Augment the technical knowledge among students and faculty members through research activities to meet industrial and societal needs.

### **Program Educational Objectives (PEOs)**

<b>PEOs</b>	<b>Keywords</b>	<b>Description</b>
<b>PEO1</b>	<b>Core Competency</b>	Graduates will adopt technological changes in core and allied areas of Mechanical Engineering.
<b>PEO2</b>	<b>Professionalism</b>	Graduates will have leadership quality with soft skills to excel in their professional career.
<b>PEO3</b>	<b>Higher Studies and Entrepreneurship</b>	Graduates will evoke interest in higher education and develop entrepreneurial attitude for ever changing industrial and societal environment.



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## Engineers develop first method for controlling nanomotors

J. Arun, II Year, Department of Mechanical Engineering, KSRIET

In a breakthrough for nanotechnology, engineers at The University of Texas at Austin have developed the first method for selecting and switching the mechanical motion of nanomotors among multiple modes with simple visible light as the stimulus.

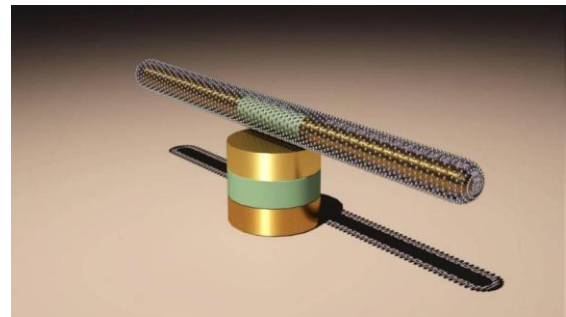
The capability of mechanical reconfiguration could lead to a new class of controllable nanoelectromechanical and nanorobotic devices for a variety of fields including drug delivery, optical sensing, communication, molecule release, detection, nanoparticle separation and microfluidic automation.

The finding, made by Donglei (Emma) Fan, associate professor at the Cockrell School of Engineering's Department of Mechanical Engineering, and Ph.D. candidate Zexi Liang, demonstrates how, depending on the intensity, light can instantly increase, stop and even reverse the rotation orientation of silicon nanomotors in an electric field. This effect and the underlying physical principles have been unveiled for the first time. It switches mechanical motion of rotary nanomotors among various modes instantaneously and effectively.

Nanomotors, which are nanoscale devices capable of converting energy into movement at the cellular and molecular levels, have the potential to be used in everything from drug delivery to nanoparticle separation.

Using light from a laser or light projector at strengths varying from visible to infrared, the UT researchers' novel technique for reconfiguring the motion of

nanomotors is efficient and simple in its function. Nanomotors with tunable speed have already been researched as drug delivery vessels, but using light to adjust the mechanical motions has far wider implications for nanomotors and nanotechnology research more generally.



"The ability to alter the behavior of nanodevices in this way -- from passive to active -- opens the door to the design of autonomous and intelligent machines at the nanoscale," Fan said.

Fan describes the working principle of reconfigurable electric nanomotors as a mechanical analogy of electric transistors, the basic building blocks of microchips in cellphones, computers, laptops and other electronic devices that switch on demand to external stimuli.

"We successfully tested our hypothesis based on the newly discovered effect through a practical application," Fan added.

"We were able to distinguish semiconductor and metal nanomaterials just by observing their different mechanical motions in response to light with a conventional optical microscope. This distinction was made in a noncontact and nondestructive manner compared to

the prevailing destructive contact-based electric measurements."

The discovery of light acting as a switch for adjusting the mechanical behaviors of nanomotors was based on examinations of the interactions of light, an electric field and semiconductor nanoparticles at play in a water-based solution.

This is Fan and her team's latest breakthrough in this area. In 2014, they developed the smallest, fastest and longest-running rotary nanomotors ever designed.

The research was funded by Fan's National Science Foundation Faculty Early Career Development Award and the Welch Foundation.

## Performance and Endurance Enhancement by Means of Turbine Cooling

S. Lavanya, II Year, Department of Mechanical Engineering, KSRIET

This article discusses how advancement in turbine cooling techniques has helped enhancing the performance and endurance of turbines. Gas turbine thermal efficiencies increase with higher temperatures of the gas flow exiting the combustor and entering the work-producing component—the turbine. The fundamental aim of a turbine heat transfer designer is to obtain the highest overall cooling effectiveness for a blade or vane, with the lowest possible penalty on thermodynamic performance. In the last 50 years, advances have led to an overall increase in turbine and vane cooling effectiveness, from 0.1 to 0.7. It started with convection only and has progressed with film cooling, thermal barrier coatings, and new materials and architectures. Temperature excesses in turbines are now as high as 1400°F (778°C) above alloy melting points. Film cooling is the key to attaining these levels, and to increasing them in the future, for yet higher gas turbine efficiencies.

Large Brayton-Rankine combined cycle electrical power plants are now at record setting thermal efficiencies of 62%, the most efficient heat engines yet perfected by engineers. These have been made possible by modern efficient (as high as 45%) electric power gas turbines whose exit gas path temperatures have been increased enough to allow ample high pressure steam production for the Rankine cycle. Aviation jet engine advances have provided much of the leading edge technology that underlies this power plant revolution

Gas turbine thermal efficiencies increase with higher temperatures of the gas flow exiting the combustor and entering the work-producing component - the turbine. Turbine inlet temperatures in the gas path of modern highperformance commercial jet engines can reach 3000°F (1649°C), while electric power gas turbines typically operate at 2700°F (1482°C) or lower, and military jets can be in the 3600°F (1982°C) range. (The turbine designer must accommodate for excursions above these nominal temperatures, due to combustor hot streaks, etc.)

In the highest-temperature regions of the turbine, special high-melting-point nickel-base alloy cast blades and vanes are used because of their ability to retain strength and resist hot corrosion at extreme temperatures. These so-called superalloys, when conventionally vacuum cast, soften and melt at temperatures between about 2200°F (1204°C) and 2500°F (1371°C).

This means blades and vanes closest to the combustor can be operating in gas-path temperatures far exceeding their melting point. To endure these temperature excesses of 500 to 1400 F° (278 to 778 C°), they must be cooled to acceptable service temperature (typically eight-to-nine-tenths of their owel melting point) to maintain integrity.

Thus, turbine airfoils subjected to the hottest gas flows take the form of elaborate superalloy investment castings to accommodate the intricate internal passages and surface hole patterns necessary to channel and direct cooling air (bled from the compressor) within and

over exterior surfaces of the superalloy airfoil structure. By turbine design conventions, internal airfoil cooling is usually termed “convective cooling”, while the protective effect of cooling air over external airfoil surfaces is called “film cooling”.

### A New Turbine Cooling Guide

This past June, at ASME Turbo Expo '17 in Charlotte, the biennial International Gas Turbine Institute Scholar Lecture was given by Ronald Bunker. Ron, a Past IGTI Chair and recently retired General Electric gas turbine heat transfer expert, presented his scholar paper “Evolution of Turbine Cooling” [1].

Dr. Bunker’s paper can now serve as an up-to-date overview of turbine cooling, complete with a listing of 123 references. His 26-page paper treats the evolution of turbine cooling in three broad aspects, including background development, the current state-of-the-art, and prospects for the future. This is indeed a seminal work by an expert, reflecting his direct research and design OEM experience over a period of several decades.

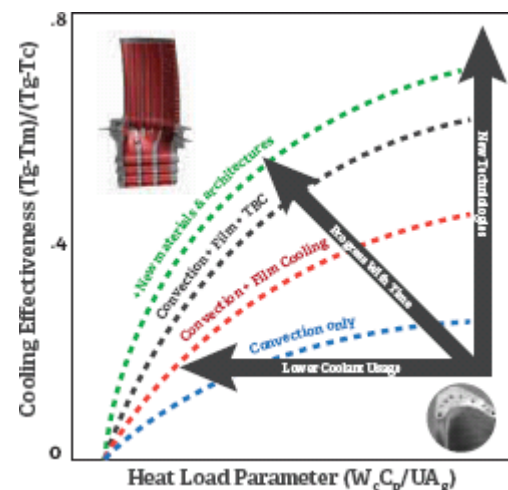
The author posits that the fundamental aim of a turbine heat transfer designer is to obtain the highest overall cooling effectiveness for a blade or vane, with the lowest possible penalty on thermodynamic performance. In Fig. 1 (taken from his Fig. 3 [1]) this is shown in the form of notional (i.e., expressing a notion) cooling technology curves.

On the Fig. 1 ordinate, the cooling effectiveness of a turbine blade or vane is made up of its bulk metal temperature ( $T_m$ ), the hot gas path temperature ( $T_g$ ), and the coolant fluid temperature ( $T_c$ ). (A value of 1.0 would represent “perfect” cooling.)

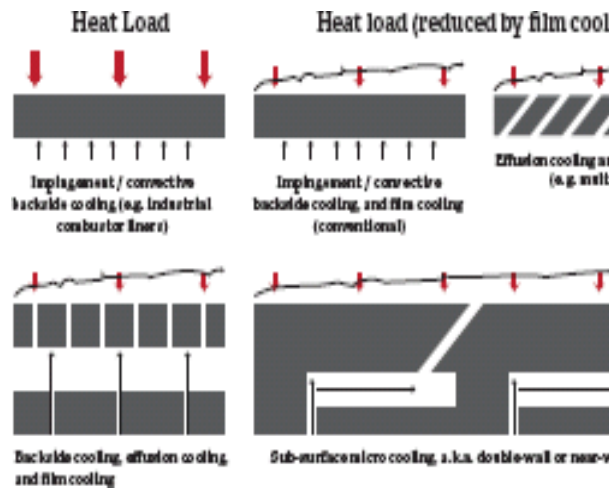
The Fig. 1 abscissa is the heat load parameter which is the external airfoil heat loading ( $UA_g$ , where  $U$  is an overall hot gas path convective and radiation heat transfer coefficient and  $A_g$  is an external surface area), divided into the coolant flow rate ( $W_c$ ) and the thermal capacity coefficient of the coolant fluid ( $C_p$ ).

Bunker points out that in the last 50 years, advances have led to an overall increase in turbine and vane cooling effectiveness shown in Fig. 1, from 0.1 to 0.7. It started with convection only (e.g., the convectively cooled turbine airfoils of the German jet engines of WWII) and has progressed with film cooling, thermal barrier coatings (TBCs) and new materials and architectures (e.g., directionally solidified and single crystal turbine blades, which entered service in the 1970-90s).

In Fig. 2 (taken from his Fig. 4 [1]) are five conventional investment casting cooling geometries in use today. They range from convection only (i.e. internal passage heat transfer only), to film cooling and the combination of both. The reader is referred to Bunker’s paper for a detailed discussion of each.



**FIGURE 2** Conventional modes of turbine blade and vane cooling.



### An Evolution Theme

In writing his ASME IGTI Scholar paper covering this fascinatingly important topic of turbine cooling, Bunker used evolution as a theme. He wrote that the evolution of turbine cooling (since the gas turbine's invention in 1939) is loosely analogous to that of the Darwinian theory of evolution for animals, starting from highly simplistic forms and progressing to increasingly more complex designs having greater capabilities. Let me continue his evolution theme to end here, with a view of the importance of film cooling for present and future gas turbine technology.

Lieberman [2] reviews current research in human evolutionary biology on the fundamental role our unique sweat cooling system has played in human evolution.

Human sweating probably emerged sometime around 2 million years ago, in order to help meat-eating hominids compete with other carnivores. Eating meat led to larger body and brain size than chimpanzees. Sweat cooling allowed our ancestors to forage safely during peak heat in a hot, dry African climate, when heat-dump limited predators were unable to hunt them. Evaporative cooling also allowed persistence hunting, where hominids (well before the bow and arrow) could wear down prey, not by superior speed, but by a sustained pace causing hyperthermic state in the hunted.

An analogy can be made between the role of sweat cooling in human evolution to that of the evolution of gas turbine performance and endurance enhancement due to film cooling. Earlier, we saw what temperature excesses are now in turbines - as high as 1400 F° (778 C°) above alloy melting points. Film cooling is key to attaining these levels, and to increasing them in the future, for yet higher gas turbine efficiencies. (Bunker [1] discusses "micro cooling", an advance form of film cooling, akin to sweat cooling.)

Four centuries ago, Ben Jonson wrote: "Who casts to write a living line, must sweat." Today, a turbine designer who casts to perfect a more efficient gas turbine, must film cool.

## Jet Engine Wing Mounting

P.Srinivasan, II Year, Department of Mechanical Engineering, KSRIET

The mounting of a jet engine under the wing of an airliner can be a daunting task for turbofan engineers.

Thrust forces generated by gas path momentum flow changes in a jet engine are transmitted by pressure (and friction) forces on stators and struts attached to the engine case. Case engine mounts then transmit the thrust forces (as high as 100,000 pounds thrust on the largest engines) to the wing pylons to pull the plane forward. The mounts must also support the engine weight (as high as 20,000 pounds) and carry nacelle flight loads.

Engine bypass ratios are increasing (12:1 on the new geared fan engines), with fan sizes ever growing (178 inch diameter fan on the new GE9X). Mounting these new engines under a wing can present new challenges.

During the early days of its introduction in the late 1960's, Boeing's iconic 747 jumbo jet had engine mount problems. These are examined, together with their solution.

As a window-seated passenger in a large airliner in flight, the view of a mighty jet engine mounted under the wing is an awe-inspiring sight for me - especially during wing-deflecting rough weather. I marvel at the engineering required for the engine mounts to keep the engine safely attached to the wing's pylon, while transmitting thrust for flight, carrying engine weight and supporting nacelle aerodynamic loading.

Bill Gunston [1] relates that the D.H. 106 Comet, the first jet liner, in 1947 pioneered

the concept of turbojets buried within the roots of its long-chord wing. A year before, Boeing with its Model 450 airplane, had jet engine pods hung on thin pylon struts well below and ahead of the wing's leading edge. Since then, airliner designers have largely followed the Boeing stratagem of underwing engine mounting.

Thrust forces generated by gas path momentum flow changes in a jet engine are transmitted by pressure (and friction) forces on stators and struts attached to the engine case. Case engine mounts then transmit the thrust forces (as high as 100,000 pounds thrust on the largest engines) to the wing pylons to pull the plane forward. The mounts must also support engine weight (as high as 20,000 pounds) and carry nacelle flight loads. Because of the wide variations in temperatures and loads on engine casings, engine mounts are both fixed and floating, to allow casings to expand and contract freely in both axial and radial directions.

### Mounting Troubles

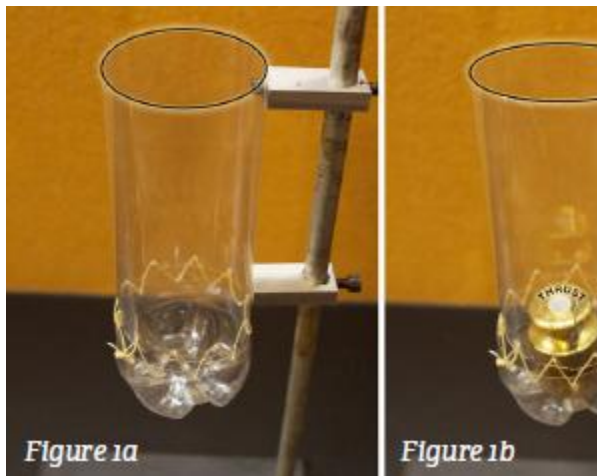
Since aircraft Number 1 had its maiden flight in 1969, Boeing's 747 was the first jumbo jet. It is the most successful wide-body passenger aircraft yet developed, with over 1,500 produced to date. As a young engineer at Pratt & Whitney Aircraft (now UTC's Pratt & Whitney) I had some personal involvement with engine mounting troubles with the 747's inaugural engine, the PWA JT9D [2].

Less than six months after its maiden flight, it was determined that the JT9D engine case was excessively bending and

ovalizing - exhibiting non-circular distortion - under thrust loading that could be as high as 43,500 pounds on takeoff. The ovalizing distortion resulted in turbine and compressor blade rubbing against the interior of the engine case and necessitated power-robbing increases in blade tip clearance gaps. The result was a serious reduction in thrust, and increased fuel consumption, as much as 7 percent above guaranteed rates.

Both Boeing and Pratt & Whitney were essentially betting their net worth on the 747, this the first commercial jumbo jet. At one time, there were 15 four-engine 747 jets sitting engineless on Boeing's Everett tarmac, representing \$360 million - more than \$2 billion 2018 dollars - of stranded assets. Getting those planes into the air was an engineering and commercial imperative.

### Mounting Fixes



The bottom is reattached with string to hold a brass weight, simulating engine thrust. The cylindrical portion of plastic container is held in place by a fixed upper attachment (an Allen screw), and a lower floating support point, to simulate the original JT9D engine mounting arrangement.

As one can see, Fig. 1a shows no distortion. When the brass weight is

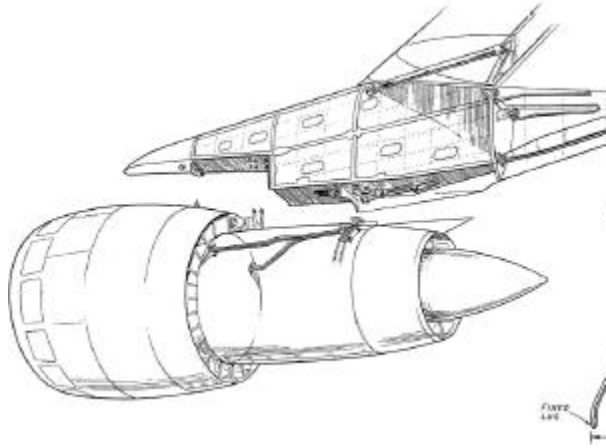
applied in Fig. 1b, ovalization is clearly visible. (Evidence of bending along the container axis is not shown in Fig. 1b and would probably require more careful measurement for verification.)

Pratt structural engineers conducted extensive static JT9D case deflection tests and analysis. They found that if two - rather than one - thrust mounting points were circumferentially located 90 degrees apart at any one axial position on the engine case, the resulting ovalization of each would cancel the other, greatly reducing overall case distortion. This two-point distortion canceling method was very effective, so much so that the two mounting points could be separated by as much as 120 degrees and still yield an acceptable amount of case ovalization reduction.

The Pratt team then devised and designed a Y-shaped titanium tubular thrust frame with arms that were fastened to the compressor intermediate case at two fixed mounts, about 120 degrees apart. The leg of the thrust frame then attached to the rear turbine case mount through an axially sliding joint (to accommodate engine axial length changes) that was rigidly affixed to the pylon. (See Fig. 2).

Subsequent engine tests showed that the new thrust frame substantially reduced ovalization. Maximum thrust could be achieved with little case distortion and engine performance now met fuel consumption specifications. The new thrust frame (which became known as the "yoke" at P&WA) added about 163 pounds of weight to the 8,600-pound JT9D, and required a relocation of several external engine components. But as an add-on to the existing FAA certified engine it solved the ovalization problem which was threatening the financial future of both Boeing and Pratt & Whitney Aircraft.

### Current Mountings



The mounting of jet engines continue to challenge turbofan jet engineers. For proprietary reasons, not much is published in the open literature, but one can go to patent listings to get an idea of the continuing technical activity in engine mounting.

Engine bypass ratios are increasing (12:1 on the new geared fan engines), with fan sizes ever growing (178 inch diameter fan on the new GE9X). Mounting these under a wing is a daunting task!

## Gears Steer New Engine Designs

S.Vasanth, II Year, Department of Mechanical Engineering, KSRIET

This article reviews the development of geared turbofan (GTF) engines. GTF engines have a hub-mounted epicyclic gearbox that drives the front-mounted fan at lower rotational speeds than the engine turbine section that powers the fan. The turbine driving the fan is most efficient at high-rotational speeds. The fan operates most efficiently and creates less noise at lower rpm. The operating gear reduction ratio also permits increasing the engine's bypass ratio with larger fans. Gear trains are one of the oldest known machines, and none is more closely identified by the general public with the profession of mechanical engineering. Pratt & Whitney is in production of their first generation of GTF engines in the 18,000–30,000 lbt range, which power twin engine single-aisle, narrow body 70–200 passenger aircraft. The GTF combines existing jet engine technology with the well-established mechanical engineering technology of gears.

### Gears Steer New Engine Designs

The coterie of geared turbofan jet engine companies is growing. Rolls-Royce is now developing a geared turbofan (GTF) for its future engines in the 25,000–110,000 pound-thrust (lbt) range, slated for production in the next decade [1]. This major OEM will join Pratt & Whitney and Honeywell, who both have been designing, developing and producing GTF engines for some years.

GTF engines have a hub-mounted epicyclic gearbox that drives the front-mounted fan at lower rotational speeds than the engine turbine section that powers the fan. The turbine driving the fan is most efficient at high rotational speeds.

The fan operates most efficiently and creates less noise at lower rpm. By lowering fan blade tip speeds by means of gearing, engineers can more easily satisfy fan blade and disk stress limits and avoid the onset of power-robbing supersonic fan blade flows.

**Figure 1** Rolls-Royce Epicyclic Planetary Gearbox (4:1 gear ratio 31 inches diameter)



The operating gear reduction ratio also permits increasing the engine's bypass ratio with larger fans. Bypass ratios - the mass of fan air bypassed around the engine for every unit mass of air through the engine - can be increased, which improves the propulsion efficiency of the turbofan engine.

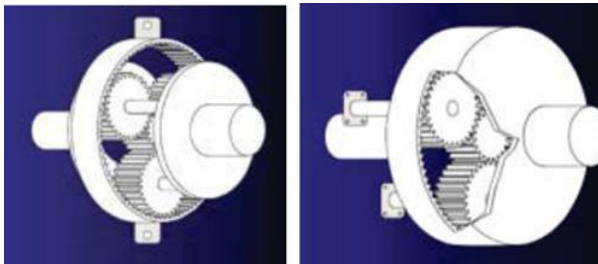
The net result is a great reduction in fan generated noise and as much as a double digit reduction in engine fuel consumption. Both of these attributes are causing airlines to demand from airframe companies, new commercial aircraft that mount the GTF engines.

## Gear Lore

Gear trains are one of the oldest known machines and none is more closely identified by the general public, with the profession of mechanical engineering. Gears use the principle of the lever to alter the speed and torque carried by shafts, and can be traced back as far as 3000 BC in use in China.

One of the most famous of ancient gear assemblies is the Antikythera Mechanism [2], recovered in 1900 from a shipwreck off the coast of Greece. Possibly constructed in Rhodes in 150-100 BC, the mechanism is an astronomical analog calculator (or orrery) that was probably used as one of the first analog computers to show celestial positions of the sun and moon, the time of solar eclipses and the dates of Olympic and Pan-Hellenic games. The Antikythera Mechanism has some 30 intermeshing gears, which include an epicyclic gear train.

So here we are, two thousand years later using the same type of gear train to improve the performance of modern gas turbines. The name epicycle goes back to Greek astronomy, where planets were believed to move in circular orbits, with the earth as center - a geocentric system. Such orbits could not explain why at times, planets moved backward, relative to the earth-bound observer. Ptolemy (150 AD) explained such retrograde motion by superposing small circles - epicycles - on the original assumed circular orbit.



Currently, a geared fan epicyclic gearbox consists of a center sun gear, mounted on the driving turbine shaft. The sun gear meshes with normatively, five equallysized surrounding pinion gears, which also mesh with an encompassing annular ring gear. A circular carrier houses the five pinion gear shafts to support and position them.

If the carrier is fixed to the engine casing, the ring gear drives the fan. The pinion gears, now fixed as they transmit motion from sun to ring gear, are now called star gears. If the ring gear is fixed the carrier rotates to drive the fan. The pinion gears now rotate about the sun gear, and are called planet gears. A planetary gearbox can have higher gear ratios than a star gearbox.

## Current Production GTFs

Honeywell first started developing geared fans almost 50 years ago [3]. In 1968, then as the Garrett Air Research Phoenix Division, they developed their 3500 lbt TFE731 business jet engine from an existing auxiliary power unit (APU). Given the high rotational speed of the APU low pressure turbine (about 20,000 rpm), to avoid excessive fan tip speeds, Garrett engineers developed a epicyclic gearbox (about 8.5 inches in diameter and with a 1.8:1 gear ratio), which allowed the TFE731 to have a 2.5:1 bypass ratio (high for 1972, when it was certified). Still in production, it has been one of the most successful small gas turbine aircraft engines, with over 13,000 units produced.

Pratt & Whitney is in production of their first generation of GTF engines in the 18,000 - 30,000 lbt range, which power twin engine single-aisle, narrow body 70 - 200 passenger aircraft [4]. As an example, their PW1100-JM is currently powering the Airbus A320neo, with airlines reporting up to 20% in fuel savings. The epicyclic gearbox (about 20 inches in

diameter) has journal bearings for its star gears rather than roller element bearings, with transmitted power as high as 30,000 hp. The gear ratio is 3:1, yielding a bypass ratio of 12:1. Even small inefficiencies in its double helical gear teeth and bearings could generate enough heat to “cook” gearbox lubricating oil. Testing has shown that the P&W GTF gearboxes must be at least 99.3% efficient to avoid that problem.

### Future Directions

One of my colleagues, Kazem Kazerounian (currently our Dean of Engineering at UConn) who is a gear systems researcher and an early consultant for P&W on gears, has some observations on possible future work on GTF gearboxes:

1. The challenges of light-weight, high-powered epicyclic gear systems include large deflections and vibration induced in the relatively thin ring gears (as the planets/ stars pass), and the

possibilities of large displacement of the center of the sun gear.

2. New developments include using Herringbone bevel gears (bevel gears of opposite directions to cancel axial thrust) and using spiral bevel gears instead of straight bevels. Additional advantages in smoothness and load carrying capacity might be obtained by phasing the two bevel gears that constitute the Herringbones, so that teeth on both sides do not enter the mesh simultaneously.
3. There is significant room for optimization if designers consider nonstandard, or even non-involute gearing. This is uncharted territory in gear design, that might decide the future leaders in GTF design and manufacturing.

New technologies evolve based on the chaotic and constant recombining of existing technologies [4]. The GTF combines existing jet engine technology with the well-established mechanical engineering technology of gears.

## Some Details of Jet Engine Thrust

K.Gopinath, II Year, Department of Mechanical Engineering, KSRIET

This article throws light on details of jet engine thrust. The momentum flux of the engine exiting flow is greater than that which entered, brought about by the addition of the energy input from combusted fuel, and giving rise to engine thrust. Thrust arises from pressure and frictional forces on these surfaces, e.g., blades, vanes, endwalls, ducts, etc. This interior force view of thrust is easy to visualize but quite another thing to actually measure. In doing research on secondary flow in gas turbine passages, researchers have measured both steady-state momentum changes and surface forces, in the much simpler case of a turbine blade cascade. The thrust values for each component in the Rolls-Royce single spool engine have been shown in this paper. It has been noted that from the compressor, gas path flow enters the engine case diffuser, where a pressure gain produces another component of forward thrust of 2,186 lbf. Newton's second law of motion allows us to examine engine component behavior that exhibits both forward and rearward propelling forces, which results in the net thrust our airline passengers have purchased.

### Article

Typically, jet airline passengers do not pause to think about it, but part of their ticket purchase is for thrust, the thrust required to fly them to their destination. Jet engine thrust is the force produced by an engine that acts on its aircraft mounts, to pull their plane forward in flight. It is readily measured by load cells when an engine is run in a test stand.

As engineers, some of us have probably been asked by non-engineers to explain

how jet engine thrust comes about. The easy answer (but usually not clear to a nontechnical person) is Newton's 2nd Law of Motion for a control volume [1], written in words as

Sum of the Forces=Rate of Production of Momentum.

(1)

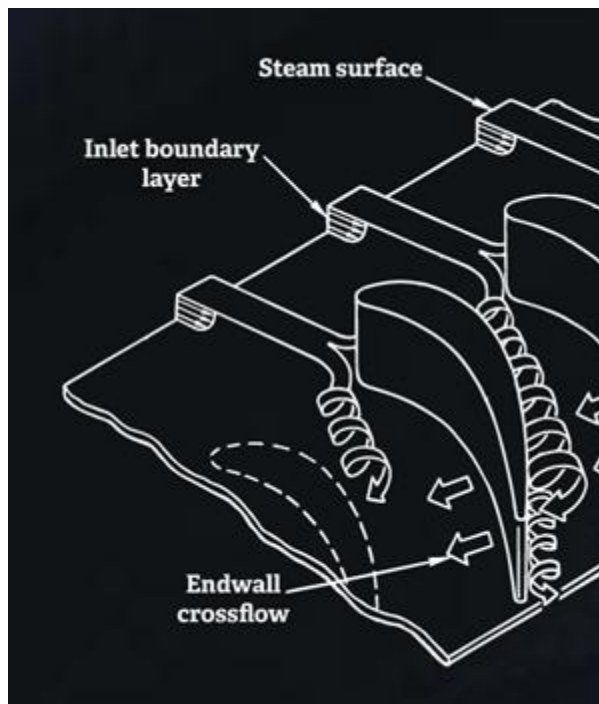
The jet engine then is a momentum augments of the air flow through the engine, to produce a forward force for flight. The momentum flux of the engine exiting flow is greater than that which entered, brought about by the addition of the energy input from combusted fuel, and giving rise to engine thrust.

### Interior Forces

One answer I have given to those not versed in Newtonian mechanics is to picture thrust as the summation of all instantaneous forces acting in an axial direction on the surfaces of engine parts exposed to gas flow through the engine. Thrust arises from pressure and frictional forces on these surfaces, e.g., blades, vanes, endwalls, ducts, etc.

This interior force view of thrust is easy to visualize but quite another thing to actually measure. In doing research on secondary flow in gas turbine passages, my former graduate student, Brian Holley (now a researcher at United Technologies Research Center) measured both  $\dot{p}$ -steady state momentum changes and surface forces, in the much simpler case of a turbine blade cascade [2], shown in Fig. 1.

**FIGURE 1** Sketch of a turbine blade cascade with an enhanced rendering of endwall secondary flow [2].



Using a five-hole pressure probe, Brian measured steady state momentum fluxes in and out of the cascade (the right hand side of Eq. (1)) in a few days. The cascade surface pressure forces were measured with an array of pressure taps, and using oil fringe interferometry (OFI), he painstakingly measured frictional surface forces (the left hand side of Eq. (1)) which took several months. This yielded a surface force field for checking against CFD calculations, as well as satisfying Eq. (1) within experimental accuracy [3].

I tell the tale to show that measurement of thrust is relatively easily attained by measuring momentum changes, but would be excruciatingly difficult to do by measuring internal surface forces in an engine.

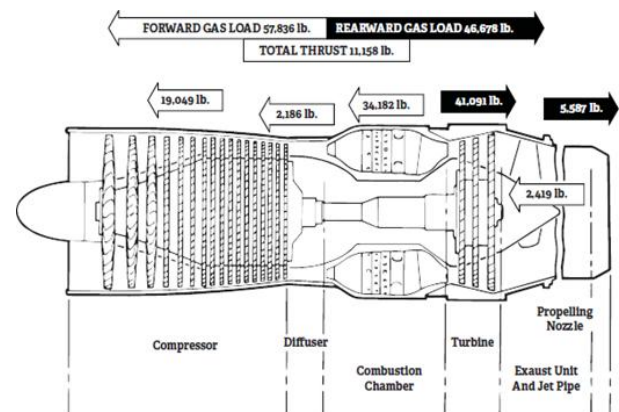
### Engine Thrust Anatomy

This sets the stage for using Eq. (1) to calculate the distribution of thrust in a jet engine itself. This will show what part

each engine component contributes to net thrust, with some surprises to those of us who might not have gone through such an analysis.

An excellent example of such an analysis is given in the very informative Rolls-Royce publication, *The Jet Engine* [4]. As shown in Fig. 2, the Rolls-Royce example consists of a single spool axial flow turbojet which has a net thrust of 11,158 pounds thrust (lbt), acting to left, for forward flight. (For comparison, most turbofan engines are in the 20,000-30,000 lbt range for single-aisle airliners, and in the 100,000 lbt range for larger airliners.)

The thrust values for each component in the Rolls-Royce single spool engine are shown in Fig. 2. The values (see [4] for details) are calculated from Eq. (1), where the mass flow rate, flow areas and pressures are given for each component, and mean one-dimensional flow is assumed in the gas path. Following Fig. 2, an inlet-to-exit analysis yields the following:



1. As shown in Fig. 2, the single spool compressor, with a compression ratio of 7.4, yields a forward thrust of 19,049 lbt (171% of net thrust of 11,158 lbt).
2. From the compressor, gas path flow enters the engine case diffuser, where a pressure gain produces another component of

forward thrust of 2,186 lbt (20% of net thrust).

3. Flow from the diffuser enters the combustion chamber, where it is heated at near constant pressure by the combusted fuel, with a large increase in exit flow area. This results in the largest value of forward thrust of any of the engine components, of 34,182 lbt (306% of net thrust).
4. The expanded combustion high temperature gases then enter the turbine (which drives the compressor) where they are accelerated and dropped in pressure and temperature, to produce a rearward thrust of -41,091 lbt (-368% of net thrust).
5. Turbine flow then enters the exhaust unit and jet pipe (Rolls-

Royce terminology) where decelerating flow yield a small forward thrust of 2,419 lbt (22% of net thrust).

6. The engine gas flow finally enters the propelling nozzle, to increase its velocity and decrease pressure. As it exhausts to the atmosphere, it produces another rearward thrust of -5,587 lbt (-50% of net thrust).

I invite the reader to sum up the individual component contributions given in Fig. 2 and in items 1-6 above, to yield the net thrust of 11,158 lbt for this Rolls-Royce single spool engine. Newton's 2nd Law of Motion allows us to examine engine component behavior that exhibit both forward and rearward propelling forces, which results in the net trust our airline passengers have purchased.

## Gas Turbine Disc Resurrection

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This article discusses various aspects and need for gas turbine disc resurrection. Depending on the record keeping system used by the government, airlines, OEMs, and users, gas turbine discs are retired before they reach a critical state that might lead to their failure. Experts have reviewed current approaches to gas turbine life management. They point out that the high reliability and safety of modern gas turbines is largely due to a combination of improved materials, conservative design and maintenance philosophies, and improved life prediction capabilities. However, there are significant safety and economic concerns involved in the use of life predictions applied to extend disc life. Another resurrection path is the question of appropriating used discs to manage safe continued operation from unexpected field damage until new discs become available. Disc resurrection may be an attractive prospect, but lots of questions need to be answered before gas turbine users adopt the practice.

### Article

In axial flow gas turbines, discs in the compressor and turbine support and position rings of rotating blades and transmit energy to or from engine shafts. Their rotational speeds and power levels are high, so that each disc, composed of an inner bore, a web and an outer rim, are made of high-strength alloys, carefully manufactured to be as defect free as possible.

Typically records are kept on operation for both aviation and non-aviation engines. Depending on the record keeping system used by government, airlines, OEMs, and users, gas turbine discs are retired before

they reach a critical state that might lead to their failure.

Gas turbine lore and legend has it that there are large warehouses storing many of these expensive used discs, particularly those from high usage applications, such as popular single aisle aircraft jet engines, many military jets, and high-sales electric power gas turbines. The thought is that many of these discs, presumably with significant life left, could be resurrected for future use. The means of resurrection might be some reliable reevaluation process (combining a new life law with testing, or a new yet-to-be discovered metallurgical procedure).

Let us look at just how feasible this concept might be. First, let us briefly consider what a disc failure can bring about. Then we can look at the disc life laws and the procedures used to retire them. We will end with an assessment of what is the possibility of their resurrection, i.e. the return of these discs to active service after their “certified” life has ended.

### A Turbine Disc Failure

In an earlier column [1], I reported on the inflight turbine disc failure of a Rolls-Royce Trent engine on Qantas Flight QF32 on November 4, 2010. The super jumbo four engine Airbus A380 had just taken off from Singapore, bound for Sydney.

About 6 minutes after takeoff at 7,500 feet altitude over the Indonesian island of Batam, the Trent 900 intermediate pressure turbine disc on engine No. 2 failed, sending engine parts shrapnel through the engine nacelle and the left wing.

Passengers saw several perforations take place on the upper surface of the wing above engine No. 2, resulting in one hole as large as 65 by 80 cm. Now powered by three of the four engines, the A380 circled to dump fuel (which was also leaking out of two wing tanks, above the failed engine). The Qantas plane then returned to Singapore, to land without thrust reversers, using emergency pressurized nitrogen to lower landing gear since the hydraulic system had been compromised by the uncontained engine failure. Controls to engine No. 1 had been damaged, so that the pilots were unable to shut it down after landing. Airport firefighters flooded engine No. 1 with foam to shut it down, further increasing the overall damage cost.

Fortunately, all Flight QF32 passengers and crew were safe and uninjured after the uncontained turbine disc failure. We can see that armed with enormous rotational kinetic energy, the disintegrated parts of a failed disc (see Fig. 1) and its blading become dangerous flying projectiles.

**Figure 1.** Recovered R-R Trent 900 intermediate pressure turbine disc segment from Qantas A380 Flight QF32. (Photo provided by Australian Air Transport Safety Bureau, courtesy of Aviation Week & Space Technology.)



### Disc Lifting Approaches

Vittal, Hajela, and Joski [2] review current approaches to gas turbine life management. They point out the high reliability and safety of modern gas turbines is largely due to a combination of improved materials, conservative design and maintenance philosophies, and improved life prediction capabilities.

However, there are significant safety and economic concerns involved in the use of life predictions applied to extend disc life. For instance, disc cracking caused by the most common failure modes of low and high cycle fatigue, creep, and manufacturing defects is difficult to predict, so that statistical methods must also be relied upon.

One probabilistic life management algorithm [2] is the Life- To-First-Crack (LTFC) approach. LTFC is based on the premise that a safe service disc life can be gotten by testing a sample of engine discs in a spin pit.

It is assured that the discs are initially defect free. To get a life standard time, a disc is removed from spin pit operation, at a time just before the appearance of a fatigue-initiated “engineering crack” greater than 0.38mm in length, with a 95% confidence. This leads to a safety procedure whereby aircraft engine turbine discs are being retired at a time when one in 1000 discs has initiated a short fatigue crack of 0.38mm. This implies that over 99.9% of these expensive, high-strength alloy discs are retired before their useful life has been expended. The 1/1000 life limit is a “safe life” approach that is considered conservative [3] and even quite wasteful [2]. (It is a possible supply source for the large warehouses referred to earlier).

An alternate, newer life management algorithm is Retirement For Cause (RFC). RFC [2] allows an aircraft engine disc to be used for the full extent of its safe

fatigue life, bypassing the conservatism of the LTFC algorithm. The new safe life is based on fracture mechanics analyses at critical disc locations, the engine service cycle and the inspection/overhaul cycle. A key element in RFC is the ability to predict crack initiation and growth in a probabilistic manner.

These very brief explanations of LTFC and RFC serve to give a flavor of two disc lifing models. These and newer life laws are used by the military, OEMs, government agencies, and gas turbine operators.

### **Disc Resurrection Prospects**

Suppose you are in charge of an MRO (maintenance, repair and overhaul) for an airline company. It has a supply of used turbine discs, stored after removal from service, based on the airline's lifing policy. You know that currently there are no metallurgical procedures to restore their life by removing any residual cracks. Should you drill holes in the used discs, assigning them to scrap, or consider their resurrection in the company's fleet?

If the company has a complete set of operating and service records on the discs and are comfortable with the OEM design criteria used to predict disc service life, you might choose to consider resurrection. Then, should you inspect all the discs for surface distress and cracks, and possibly test one to failure in a spin pit? What is the company's liability if an accident occurs, caused by a failure of an resurrected disc engine?

1. Please note that a disc failure is a disc failure. The incident I chose here was probably not due to a disc life issue.

These are some of the considerations to be made if used discs are to be returned to service after their certified life. Another resurrection path is the question of appropriating used discs to manage safe continued operation from unexpected field damage until new discs become available.

As the reader can see, disc resurrection may be an attractive prospect, but lots of questions need to be answered before gas turbine users, be they military, airlines, or non-aviation, adopt the practice.

## Fracture Toughness of Titanium Foam Using Finite Element Crushable Foam Model

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Titanium foam is considering an important competitive in bio-system applications, this is due to its compatibility as well as fascination. Getting good sufficient data about fracture and mechanical properties are needed demand for scientific and Engineering works in the field of biomaterial and bio-system. Fracture toughness is measured numerically using J-integral finite element method based on crushable foam model. Three-point single notch bending specimen is used for the foam of 62.5 %, and 65 % porosity to measured surface release energy  $G_{IC}$ . this test is considered a stander test for linear material. it is found to be (2.3), and (1.36)  $\text{kJ/m}^2$ , for 62.5% and 65 % porosity respectively. this is usually used in human implants. The measured  $G_{IC}$  is acceptable compared with that experimentally measured in other published paper.

Nowadays metal foam has an attractive and competitive role in many applications such as in aircraft, shock absorber, structural components, sound and damper and in bio-systems implants and heat exchangers. The foam superior distinguished properties such as high specific stiffness, low density, and high specific strength put it in the front role of bio-material material and give its important.

Titanium foam is one of most famous metal which play dominated role in biomedical implants where biocompatibility is a great demand. This is due to its high increase of interface coefficient of friction with between bones. While the titanium foam has the advantage of reducing the stress shield effect by

varying porosities. Finite element modeling implements in designing the dental locations, measured stress which may be subjected and stop on the defects may face the implant before it inserts in the human mandibular Tanwongwan and Carmai implement crushable finite element model to obtain both compressive and flexural strength of titanium foams with different densities, the model gave acceptable results but not give complete information about plasticity behaviors.

Korim et al measured both compressive and flexural strength and stiffness using finite element analysis based on crushable damage model and gave a complete description for plasticity. The results were in good and acceptable.

Many other models work on either metal foam simulation using finite element method or titanium or even aluminum foams.

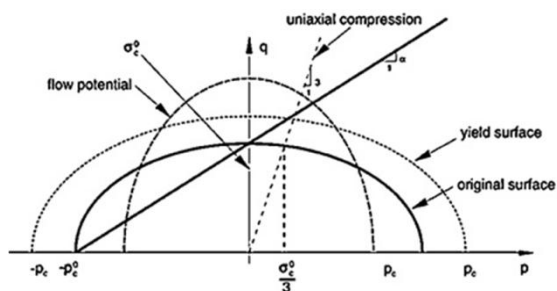
The main goal of the present study is measure fracture release energy  $G_{IC}$  of titanium foam for single edge notch three-point test specimen using crushable foam model implemented in finite element subroutine. The model description is completely detailed in this paper.

The paper is structured as follows: firstly, the crushable damage model of foam material will be outlines, Secondary, finite element domain with problems, boundary conditions and mesh domain are explained. Finally, the model results and conclusion are summarized.

## Mechanical Behaviors of Metal Foams

The foam material is distinguished by its microstructure other than solid material. Spongy microstructure in foam presented by pores or cells. At Microstructure level, metal foam characterized by relative density, cell shape, cell topology and cell size. The mechanical response affects by the internal microstructure, the compressive behaviors of such metal give three regions; linear elastic zone, a stress plateau zone, and finally the failure zone. Metal foam can deform up to large strain before full densification occurs.

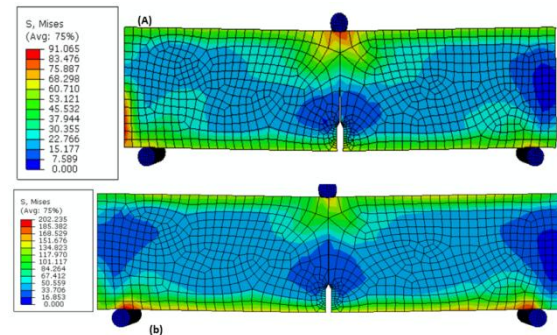
### Crushable foam model with isotropic hardening: yield surface and flow potential in the p–q stress plane



### The Single Notch Three-point Bending Domain

The single notch three-point bending test of Ti-foam is simulated with the material module listed in. Finite element domain of three dimensional of the single notches three-point bending test is constructed as shown in Figure 3. The upper movable roller is loaded by 1mm displacement while the lower rollers are fixed. C3D8R (5238 elements): An 8-node linear brick, reduced integration, hourglass controls are used. The friction coefficient between the contact surfaces is set to be 0.5. The mechanical properties of Ti-foam specimen for three-point bending test are taken from crushable model equations, which are listed in illustrates the mesh domain of three-point bending test while

shows the Boundary condition of the three-point bending test and Interaction module between supporting and load rollers.



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