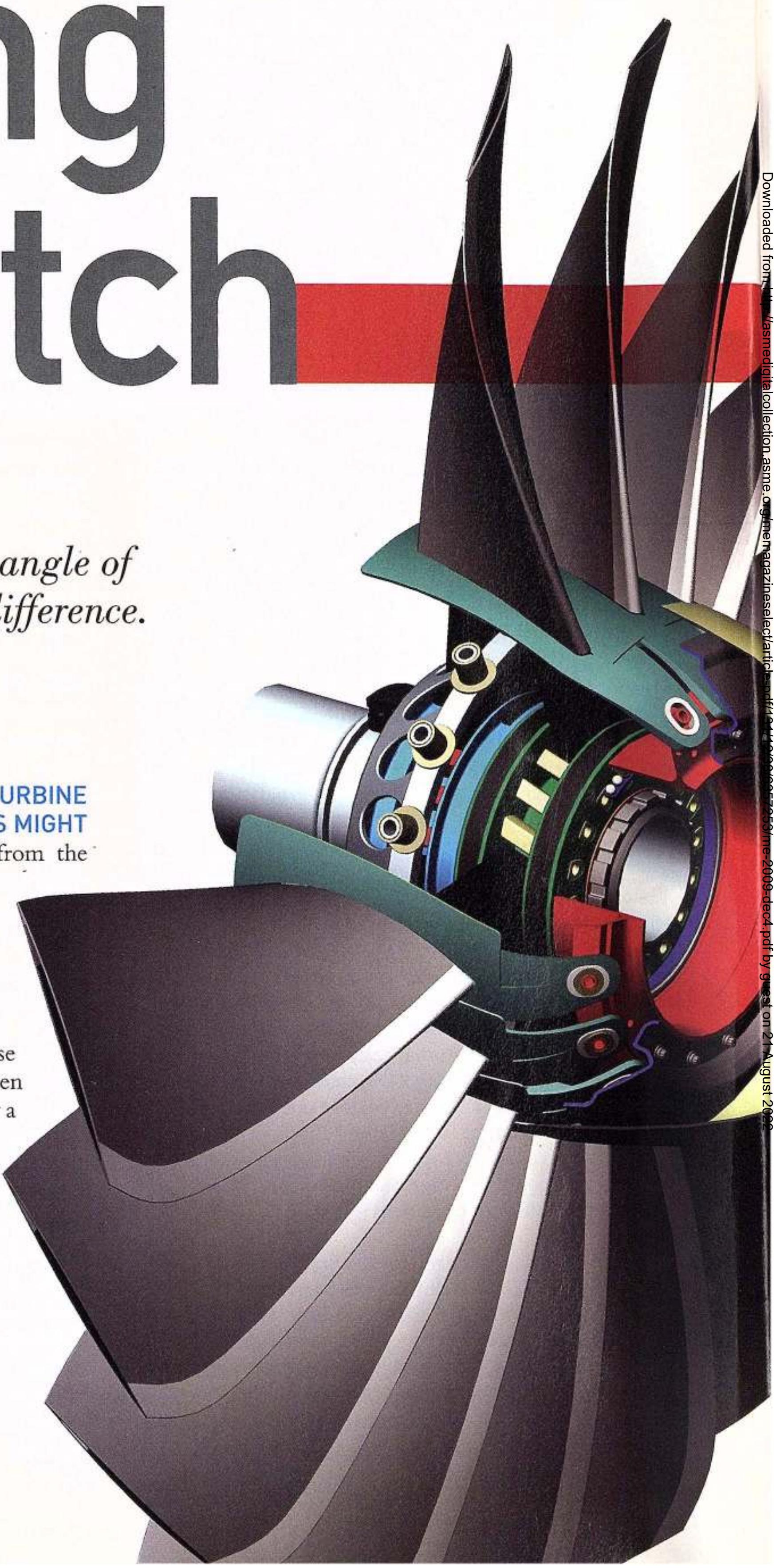
fitting a pitch



For turbines of all sorts, the angle of attack makes an enormous difference.

By Lee S. Langston

THE CONSTANT PURSUIT FOR GAS TURBINE EFFICIENCY ON THE PART OF ENGINEERS MIGHT SEEM A LITTLE... OBSESSIVE. But data from the Air Transport Association puts that obsession in context: in the summer of 2008, fuel accounted for more than 35 percent of airline operating costs. Even in times of lower fuel costs, some 15 percent of airline operating expenses are due to fuel.

So even a few percentage points of increase in fuel efficiency can be the difference between profit and bankruptcy for an airline. That's why a new turbofan engine system being developed by a small start-up company in Connecticut is generating some excitement. Analysis of this new system suggests that it could lead to as much as a 14 percent reduction in fuel consumption relative to today's turbofans.

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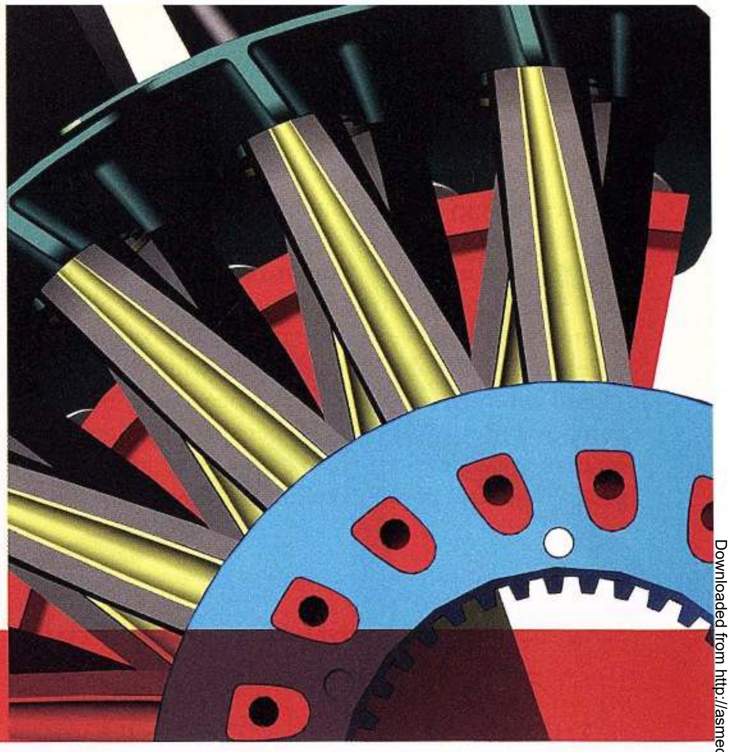
The key to this greater efficiency is an essential but often unappreciated aspect of turbomachine design: pitch. Designers of gas turbines, wind turbines, and even airplane propellers know that no single pitch angle works best under every condition. But building machines that can change the orientation of their rapidly rotating parts is a challenge.

To an engineer, the pitch of a turbomachinery blade is the angle at a representative blade cross-section between the blade chordline and the plane of the blade's rotation. Like airplane wings, turbomachine blades are characterized by a chordline, which is a straight line drawn through the foremost point on the blade's leading edge and the rearmost point on its trailing edge.



In the variable pitch fan for a turbofan engine, the timing ring (red) rotates to change blade pitch. At right, fan blade leading edge straps attach to the retaining ring (blue).

Getting the right pitch to turbomachinery blading is key to efficiency and successful operation, much as musicians strive to get the right pitch with their instruments. Before the start of a concert, members of a symphony orchestra all tune their instruments to the sound of a note—440 Hz—from the oboe. Likewise, engineers adjust a turbomachine blade's pitch angle (or simply, pitch) to control the production or absorption of power.

AIRCRAFT PROPELLERS, WIND TURBINES, AND GAS TURBINES HAVE DIFFERENT FORMS AND FUNCTIONS. But all are axial flow turbomachines. They are, in essence, a collection of rotating, fluid-turning blades that either add to or remove power from a fluid stream, depending on the mission of the machine. But as the fluid environment in which these blades turn or the amount of power to be added or extracted can change, controlling the pitch of the blades can keep these turbomachines operating at peak efficiency.

Consider the case of the aircraft propeller. When powered flight began with the Wright brothers more than a century ago, propellers were mounted with their blades in a fixed position, directly on a hub attached to the propeller shaft. But the conditions throughout a typical flight change widely, and a propeller optimized for one part of the flight cycle would be ill-suited for another. By the 1920s, however, the controllable pitch propeller was developed, which greatly increased the propeller's efficiency during a flight cycle.

Nowadays, propeller blade pitch adjustment occurs through either the action of an electric or hydraulic control unit integrated within the propeller hub. At takeoff, the pilot (or an automated control system) can set the propeller blades at a lower pitch angle. This yields less drag and allows a higher rpm to generate greater blade lift—and greater thrust at the lower takeoff velocities. In flight, at cruise conditions the pilot can then set a higher propeller pitch angle with a lower rpm to increase efficiency.

The VPF fan blade is supported by two carbon fiber straps and a cradle (green) which pivots the blade for pitch control.

ROTATING COMPOSITE TECHNOLOGIES

Should an engine fail, the pitch angle can be increased to a nominal 90 degrees, to "feather" the propeller and eliminate drag from windmilling. Likewise, propeller pitch angles can be adjusted through zero, to negative values, forcing air forward. This brings about negative thrust to slow the aircraft after landing or to allow the plane to taxi in reverse.

While engine-driven aircraft propellers impart kinetic energy to incoming flow to develop a thrust force, wind turbine blades use the kinetic energy of the wind to produce a lift force to generate mechanical power. The first windmills, which date back several thousand years, were no doubt inspired by sailboats. Indeed, the terminology of old windmills is quite similar to that of sailing, with rigging and spars and trimming the sails. And the key insight that the makers of the first windmills must have had is that the wind can be harnessed to propel an object—a wind sail or a sailboat—in many different directions, not just with the wind.

Until recently, windmills have been used mostly to pump water or to turn millstones that grind grain, but modern wind turbines are used to drive generators to produce electric power. Typically they are three-bladed horizontal-axis machines mounted on a vertical tower with an electric generator nacelle at the top, behind the hub of the turbine rotor. Large wind turbines are in the 500 kW to 4 MW output range, with rotors between 40 and 120 meters in diameter and rotation rates of five to twenty rpm. (Currently the largest is rated at more than 7 MW, with a 126-meter rotor diameter.)

> “Should the pitch control fail in a high wind situation, the turbine might damage or even destroy itself.”

In recent years, wind turbine production has soared; one major manufacturer saw its sales increase by a factor of five between 2004 and 2008. Currently the United States has less than 1 percent of its electricity generated by wind, but that share is growing. Germany, an early advocate of wind power, presently gets about 6 percent of its electricity from wind turbines, which have a nameplate capacity of 20 percent of the country's installed electric generation. (The difference reflects the intermittent nature of wind.)

Wind speed is, of course, variable, and thus wind turbines must operate over a range of wind velocities. There is roughly an order of magnitude between the cut-in speed—the lowest wind velocity at which useable electrical power is generated (usually 3 to 5 m/s)—and the cut-out speed, some 25 to 30 m/s, beyond which the wind turbine may be damaged.

Both the power generation and the wind turbine rotor speed are controlled by adjusting the blade pitch angle. As with the aviation propeller, wind turbine pitch control is achieved by either a hydraulic or an electrical mechanism mounted in the rotor hub assembly, to rotate all blades simultaneously about their axes. A separate yaw control keeps the rotor blade assembly pointed into the wind.

When the wind velocity approaches the cut-off speed, the pitch control mechanism rotates blades to an effective pitch angle of 90 degrees—that is, into a position of zero lift with the blade chordline aligned with the wind. Engineers who work on wind turbines call blades in this feathered position "furled," a nodding reference to the era when wooden and canvas windmill blades were called sails. Should the pitch control fail to furl blades in a high wind situation, the wind turbine might then over-speed and damage or even destroy itself. (Videos of such failures can be found on the Internet.)

Recently, a 2.3-megawatt wind turbine with a rotor diameter of 82 meters was mounted on a buoyant spar tethered in deep water off the coast of Norway. In this location, a turbine can take advantage of the North Sea's faster, steadier winds. The turbine, called Hywind, is part of a project to see if generating wind power from floating platforms is practical.

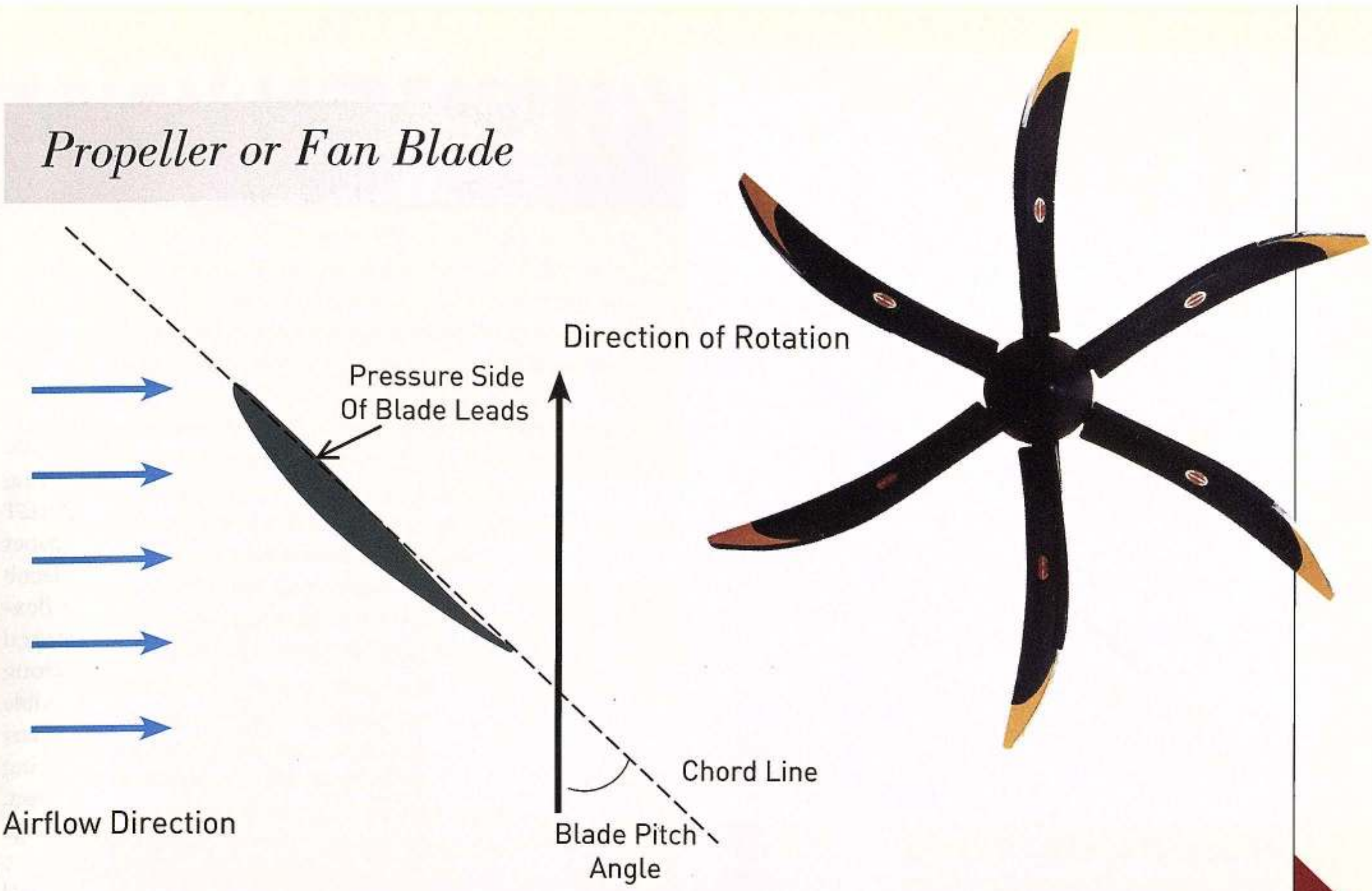
One challenge to the Hywind engineers is that the floating spar is subject to fore-and-aft and side-to-side motion from waves. This swaying motion, and the stresses induced on the structure, will be compensated by pitch control of the rotor blades, using computer software designed to measure the success of previous pitch angle changes to calculate changes in response to future wave motion. Thus, during normal operation, getting the right blade pitch is critical for both efficient electric generation and for maintaining the structure of the Hywind wind turbine itself.

GAS TURBINES CAN EITHER PRODUCE THRUST POWER, LIKE A PROPELLER, OR TURN ELECTRIC GENERATORS, LIKE A WIND TURBINE. An axial flow gas turbine consists of many rows of rotating blades, interspersed with rows of stationary airfoils, called vanes or stators. The gas turbine compressor (whose first row of rotating blades in a jet engine may be a fan) draws in air, which after passing through a combustor to add energy to the air flow, powers the turbine which drives the compressor.

For the most part—and for obvious reasons—the hundreds of blades and vanes in a gas turbine are fixed, at pitch angles determined by the designer. Performance could be enhanced by active pitch control, but how does one do this for a rotating machine as complex and as compact as a gas turbine?

A couple of approaches have been tried. The first successful mechanism to vary gas turbine airfoil pitch angles was invented by Gerhard Neumann, a General Electric engineer in the early 1950s and, later, head of GE's aircraft gas turbine division. Neumann's variable pitch compressor stator changes compressor stator or vane pitch angles by ten to thirty degrees during a flight cycle, so that both engine performance and fuel consumption are improved. Today, most axial flow gas turbines incorporate the compressor vane pitch angle control afforded by Neumann's variable stator mechanism.

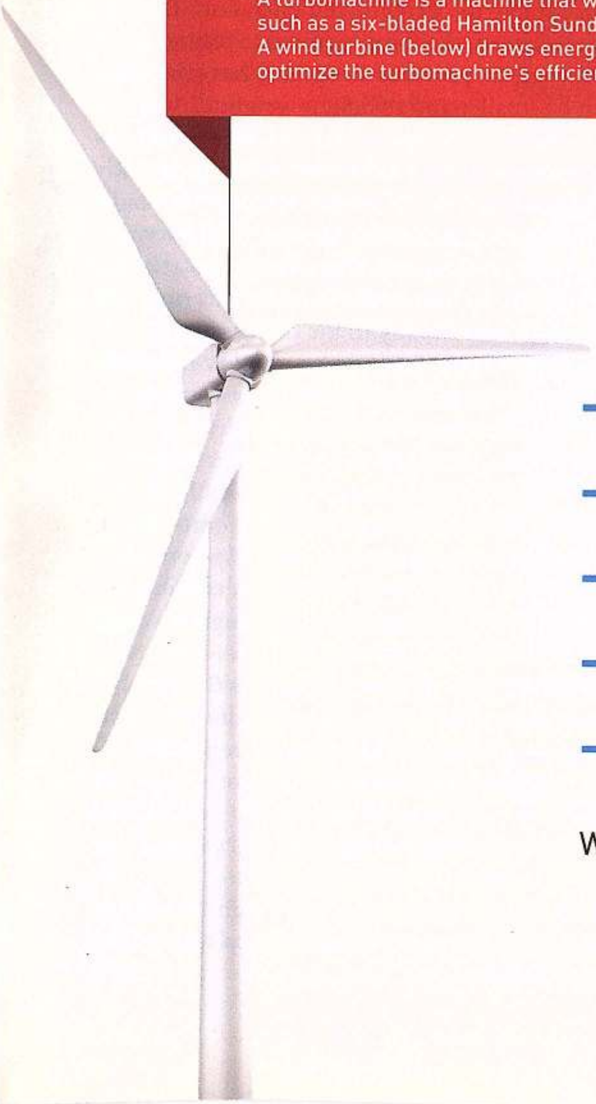
Propeller or Fan Blade

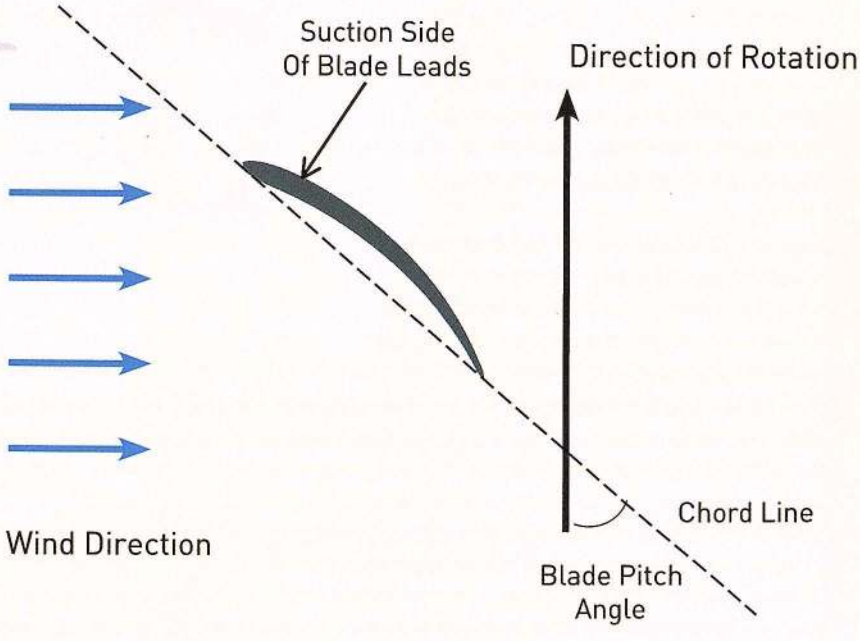


HAMILTON SUNDSTRAND

A turbomachine is a machine that works to add or extract energy to or from a fluid stream. A propeller or fan blade, such as a six-bladed Hamilton Sundstrand 568F variable pitch propeller (above), is designed to increase air speed. A wind turbine (below) draws energy from the wind to turn a generator. In either case, changing the pitch angle can optimize the turbomachine's efficiency.

Turbine Blade





HAMILTON SUNDSTRAND

The Hamilton Sundstrand 568F variable pitch propeller, shown mounted on an ATR42-500 turboprop aircraft, changes pitch over the course of a flight.

Most modern commercial jet engines are turbofans, with a front mounted fan, whose size is indicated by the bypass ratio. With a large frontal area, the commercial turbofan is designed to produce peak thrust at takeoff speeds, with most of the thrust produced by air drawn in by the fan that bypasses the engine itself. A typical bypass ratio is 6:1—six pounds of air are bypassed for every one pound that passes through the engine core.

As the bypass ratio is increased, engine fuel consumption goes down. At present, the highest bypass ratio is about 8.4:1 with GE's 100,000-pound thrust GE90 engine. Pratt & Whitney is developing a geared fan design (see "Changing the Game," May 2008) that could increase bypass ratios to 11:1.

As the bypass ratio is increased, optimally the designer will drop the fan pressure ratio to maximize propulsive efficiency. Reducing the fan pressure ratio, however, makes it difficult to optimize the fan blade pitch for both low and high flight speeds. The obvious solution is to develop fans with variable pitch blades, which would enable higher bypass ratios and a commensurate drop in engine fuel consumption.

During the 1990s jet engine companies developed and tested variable pitch turbofans, with cycle studies showing between 6 and 14 percent fuel savings. Unfortunately these early designs had variable pitch mechanisms that were too heavy and bulky. They also required hundreds of horsepower to change the fan blade pitches. (Fans typically have 20 to 40 blades, though some newer engines get by with fewer.)

In the last few years, however, Rotating Composite Technologies in Kensington, Conn., has come out with a unique patented design for the variable pitch fan that promises to overcome the deficiencies of those tested in the 1990s.

RCT is headed up by two veterans of Hamilton Standard (now Hamilton Sundstrand), the well known propeller manufacturer. John Violette, RCT's president and inventor of the variable pitch fan, and VP Harry Griswold are now working with jet engine companies to develop and test RCT's VPF.

The variable pitch design features a composite fan blade, based on RCT's extensive experience in manufacturing composite aircraft propellers. Performance of the RCT variable pitch fan was described in a recent SAE paper by Robert Mazzawy of Trebor Systems Inc. and Jacob Virkler of RCT. The blades are supported on two flexible composite straps. The straps, which are an integral part of the blade, are made of carbon fiber and are strong enough to safely support the centrifugal load, yet flexible in torsion. The straps are angled such that the blade centrifugal load is directly along each strap, thus balancing high centrifugal twisting moments at a neutral position. This greatly reduces the force required to hold or change fan blade pitch.

The two flexible straps allow the blades to be nested close together, which means the hub (or centerbody) can be sized comparably to current fixed pitch fans. Because the loads are balanced, the force required to change pitch is much less than in previous designs. Thus, the pitch actuator can be smaller and of lighter weight.

A cradle is added to the base of each blade, which provides a center pivot, and also ties each blade torsionally to the pitch change system. The top portion of the cradle forms the flow path between the blades. The lower part protrudes forward, and has a slot that attaches to a timing ring. The pitch change system then rotates this ring, and all blades move synchronously to the desired pitch.

The part of the cradle around the pivot is frangible, to absorb energy during a bird impact, and to allow for necessary blade deflection in such an encounter.

As a safety feature, either of the two straps is capable of supporting the full blade centrifugal load. That provides protection from blade loss. If pitch control is lost, the centrifugal twisting forces and the strap torsional/bending forces will balance with the blades moving to a prescribed neutral position, similar to the angle at which fixed pitch fans are built today.

Engine cycle analysis performed with RCT's design indicates that successful implementation of their variable pitch fan in turbofan engines could result in a 12 to 14 percent reduction in fuel consumption relative to today's turbofans. Importantly, this result accounts for aircraft installation effects during a typical commercial flight cycle.

If these fuel savings could spread through the airline industry, changing the pitch could lead to air carriers singing a happier tune. ■