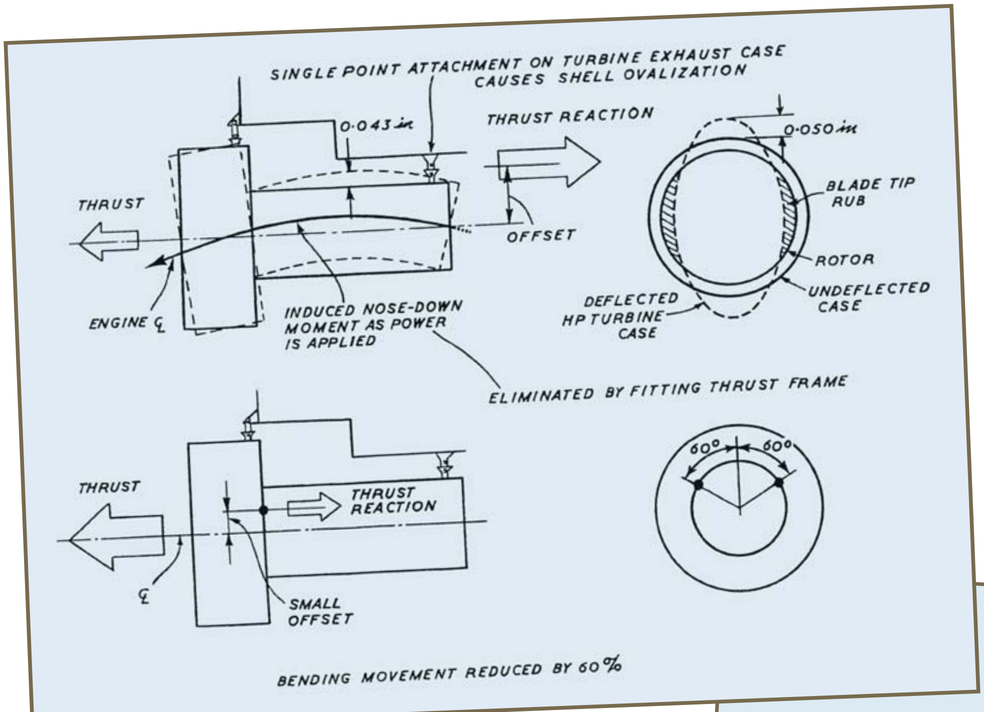
Mounting Troubles

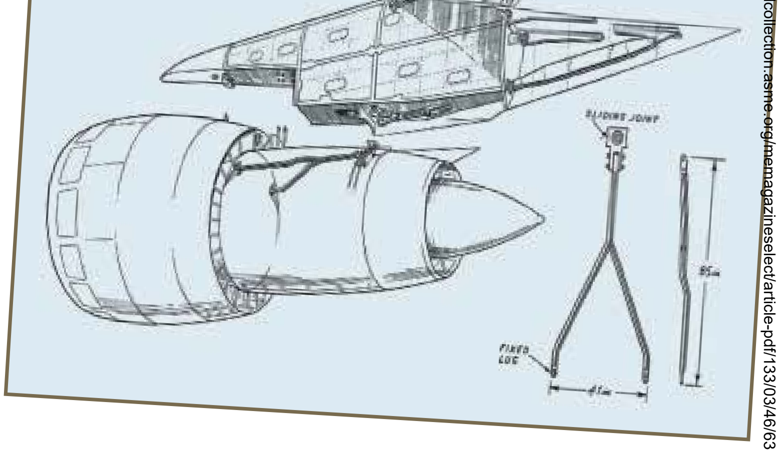
BY LEE S. LANGSTON

Lee S. Langston, an ASME Fellow, is professor emeritus of the Mechanical Engineering Department at the University of Connecticut in Storrs. He is a member and a past chair of ASME's International Gas Turbine Institute.

The first jumbo jet was an engineering marvel. But it took some clever design work to keep the planes in the air.

A Pratt & Whitney Aircraft JT9D jet engine in its nacelle being mounted on the left wing pylon of No. 1 Boeing 747, September 4, 1968.





« Flight International's diagrams showing the original ovalization problem and final solution by redistribution of the main thrust load.

» Flight International cutaway drawing showing Y-shaped thrust frame and its mounting on the P&WA JT9D.

BOEING COMPANY

FLIGHT INTERNATIONAL

It is every engineer's dream to design an icon—something so well designed and commercially successful that it is the standard to which everything else in that class is compared. Small, inexpensive automobiles, for instance, are held up to the example of the Volkswagen Beetle. More recently, every smart phone is matched against the form and function of the iPhone.

Perhaps the largest mass-produced icon is the Boeing 747, the first true jumbo jet. Since aircraft Number 1 had its maiden flight on February 9, 1969, the 747 has become the most successful wide-body passenger aircraft ever developed. Its various models, both passenger and cargo, are still in production over 40 years later, with over 1,400 assembled and flown out of Boeing's 747 plant in Everett, Wash.

And yet, when engineers were creating this modern masterpiece in the 1960s, they ran into some formidable problems. Indeed, less than six months after that maiden flight, the plane became a source of anguish for Boeing and its jet engine manufacturer, Pratt & Whitney Aircraft of East Hartford, Conn. As *Time* magazine reported in September 1969:

"On the apron outside Boeing's plant in Everett, Wash., 15 enormous 747 jets stand high and silent, harbingers of a new era in aviation. They are painted in the colors of several international airlines: TWA, Pan Am, Lufthansa, Air France. For the moment, however, the planes are the world's largest gliders —because they have no engines. Pan Am had been scheduled to get the first three commercial giants, each with a capacity of 362 passengers, in late November. Last week embarrassed Boeing officials said that performance difficulties in the Pratt & Whitney JT9D engines would delay that delivery as much as eight weeks."

Both Boeing and Pratt & Whitney were essentially betting their net worth on the 747, the first commercial jumbo jet. The 15 four-engine 747 jets sitting engineless on the Everett tarmac represented $360 million—more than $2 billion in 2010 dollars—of stranded assets.

Getting those planes in the air was an engineering and commercial imperative.

In the 1960s, the jumbo jet—a wide-body aircraft with two aisles and up to ten seats per row—was the logical next step in the progression of the airliner. In addition to Boeing, Douglas Aircraft was developing its DC-10 and Lockheed was working on what would become the L-1011 TriStar. But engineering such a large aircraft was unexpectedly challenging, and engine manufacturers ran into trouble.

Rolls-Royce, for instance, was developing the RB211 for the three-engine Lockheed L-1011. To save weight, the fan on the RB211 was built of what was then a new material—a carbon fiber called Hyfil. During certification-required bird ingestion tests, the Hyfil fan failed, shattering into pieces. That failure wound up bankrupting the company in 1971.

For the Pratt & Whitney JT9D, which was causing the 747 trouble, the engine skin casing was both 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.

Evergreen Aviation and Space Museum in McMinnville, Ore., has a thrust frame JT9D engine on display, under the huge wing of the Hughes Flying Boat (H-4) Spruce Goose (which was powered by eight P&WA R-4360 4000 hp 28-cylinder radial piston engines).

The Y-shaped thrust frame shown mounted atop the Evergreen JT9D engine.

EVERGREEN AVIATION AND SPACE MUSEUM

Problems like this weren't supposed to happen. Pratt & Whitney Aircraft had been a successful maker of jet engines for decades—in the 1950s and 60s the company had manufactured over 90 percent of the engines used in commercial aircraft. These included engines such as the JT3D on Boeing's 720 and 707, and the JT8D on the 727 and 737.

What was different about the JT9D?

The engine casings on the earlier engines were cylindrical and tube–like. Thrust forces from the engine were transferred to the airframe by one single thrust mount on the rugged compressor intermediate case and other floating mounts were located rearward on the turbine case to help carry engine weight and support maneuver loads. With this mount system the engine case was able to maintain a near circular cross section under full thrust loads.

These existing commercial aviation turbofan engines had bypass ratios between 1:1 and 1:2. The JT9D engine, on the other hand, needed a new case design to accommodate a large front-mounted fan with a bypass ratio of 5:1. Air drawn into the JT9D by the ducted front mounted fan divides into one part that flows out of the fan into the jet engine itself and five parts that bypass the engine.

The lower velocity bypassed air combined downstream with the higher velocity engine exhaust to produce thrust that had a larger mass flow (but at an average velocity lower than that of the higher velocity jet flow) in order to provide higher propulsion efficiency.

This bypass arrangement allows for lower noise and lower fuel consumption for a given thrust level. It's a concept that is still progressing: today's bypass ratios are as high as 8.4:1 and will go up to 11:1 with geared fan technology being developed by Pratt & Whitney.

Because of its large front fan diameter the JT9D needed a case with a radically different geometry than the tube that had been the design for all previous jet engines. Pratt & Whitney engineers came up with a case shaped like a fat-stemmed sunflower. The front fan and its surrounding fan case duct constituted the sunflower and the rest of the jet engine case was the stem.

Boeing chose to mount the JT9D engines well forward of the 747 wing leading edges. Reasons for doing so include the safety requirement necessitated during an emergency wheels-up landing. For such an event, forward mounted engines are positioned to break free, to be thrown up over the wings rather than punching through wing fuel tanks to possibly cause devastating fires. According to a 1969 article in *Flight International*, Boeing engineers also determined a well-forward engine position reduced nacelle-wing interaction drag forces and minimized potential wing flutter problems.

To save pylon structural weight Boeing specified that the JT9D single-thrust link to the pylon be turbine case based, rather than following the previous practice of a compressor intermediate case mount. That was a key factor that led to the turbine case ovalization problem.

I was a young engineer at Pratt & Whitney Aircraft at East Hartford when the JT9D engine case distortion came to light. When a major problem like this occurs, an engine company will try multiple paths to find the cause—and the cure. In my own case, I worked with an engineering team on an investigation of possible thermal effects that might be causing the turbine case distortion. This multiple path approach ended when it became clear that the distortion was a structural problem, caused by the position of the main thrust mount on the turbine case.

Under flight thrust loading, the engine case was bending and ovalizing. Ovalization is the cross-sectional deviation of the engine case from circular to elliptical, with the ellipse major axis passing through the turbine case thrust mount and the engine centerline axis. Engine tests showed that as much as 0.05 inch ovality was occurring at the 50-inch outside diameter high-pressure turbine case. That was enough to cause severe blade rub and subsequent serious performance-robbing blade tip clearance.

Heinz Lenkeit, a retired Pratt & Whitney structural engineer, recently told me that it was finally determined that a thrust bending moment was the cause of the distortion. The bending moment arm was equal to the turbine case mount radius, with the equal and opposite couple forces composed of the engine thrust acting as an effective force along the engine axis in the direction of flight, and the reacting force at the outer diameter of the turbine case.

This bending moment caused the JT9D engine case to both bend (as a beam might along the engine axis) and ovalize. Various modifications, such as case stiffening rings and pre-ovalized turbine seals capable of being abraded were tried, but to no avail.

Lenkeit and his fellow structural engineers conducted extensive static JT9D case deflection testing and used a Fourier analysis to treat the asymmetric case loading. 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. This Y-shaped thrust frame—described in detail in the 1972 U.S. Patent 3,675,418—thus used a two-point thrust mount on the engine compressor case to transfer thrust to the pylon at the rear of the engine, satisfying Boeing requirements. One should note that it indeed was a thrust transferring device, and was not an engine case "backbone" stiffener.

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.

The successful resolution of ovalization problems encountered in mounting the JT9D to the first Boeing 747s has provided guidance for future installations of large fan commercial jet engines. For instance, the ovalization-canceling two-point mounting design is used in the engine mounts of both the General Electric GE 90 and the Rolls-Royce Trent 800 turbofan engines that power the Boeing 777.

R.R. Whyte once wrote, "Progress is the art of getting out of trouble you wouldn't have been in if it was not for progress." Without the ambition of engineers to create a technological marvel—the veritable icon that is the Boeing 747—the issue of engine case ovalization would never have arisen. And with the innovative engine mounting solution hit upon by the engineers at Pratt & Whitney Aircraft, the whole class of jumbo jets became viable. ■

Many Boeing 747s awaiting jet engines at Paine Field, Everett, Wash., in 1969.

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