

From Fordsons to Jets: A Designer's Journey

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ABSTRACT

The remarkable evolution of the gas turbine engine has made the world much smaller and provided power for worldwide use. I often think of growing up in a farm environment, being fascinated with machinery and then having the opportunity to take part in the design and development of the world's most complex product. I worked with brilliant engineers and experienced the transition from slide rules and "hand calculation" methods to computers and more precise finite element modeling. Perhaps this story will present insight for current and future design engineers who create the manufactured products used by mankind.

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The Fordson Tractor and Me

I doubt that many have ever heard of a Fordson tractor (Figure 1). I grew up on a small farm and we used these old obsolete tractors for every task during the 1930's and even during WWII when new farm equipment was scarce.



Fig. 1. William Koff on 1930 pneumatic tire Fordson (1939)

When I was 8, my father showed me how to operate one of these by using two feet on the clutch lever to shift the three speed gearbox.

The standard tractor wheels shown were used for plowing and for pulling a disc harrow to shred the soil. Larger narrow steel wheels were used for cultivating between crop rows. A wishbone guard extension was attached behind the mudguards to prevent the tractor from raising the front wheels off the ground and overturning during a hard pull... After a number of fatalities, plowing was always done using the standard wheels with mudguards.

These four cylinder tractors were started by cranking and used a dry cell battery and coil boxes to provide current to the sparkplugs. The flywheel had magnets bolted to the rim and once the engine was started, a switch was used to change over from the starting circuit to the more powerful magneto. However, as the clearance between the rotating magnets and stator increased, there was a power loss. It was a major time consuming job to shim the flywheel magnets to reduce the clearance.

Even at a young age, I learned that machinery tolerances and clearances played an important role. I became totally enthralled with machinery while helping my father keep these old tractors operational. By the time I was 12, I had my own tractor and plowed gardens for neighbors. I also learned how to rebuild motors with new piston rings, wrist pins, re-babbetted con rod bearings, lapping the valves in and timing the magneto. I learned about fuels the "hard way". If the tractor was started on gasoline and then switched over to kerosene, you needed to switch back to gasoline before shutting down. It was not possible to start these motors with

cold kerosene in the carburetor. The Ford designers anticipated problems and provided petcocks on the carburetor for draining the fuel.

During the 30's the famous chain drive "Bulldog" Mack trucks with solid tires became obsolete. My father had a Bulldog and I will never forget the very hard jolting ride. For \$5, my father took the very powerful compact magnetos off the trucks in the junk yard. Some enterprising company had produced a magneto attachment for the Fordson so these magnetos could be installed. This eliminated the need for the starting coil boxes and battery as well as the troublesome built in flywheel magneto.

Once this was done, the engines roared with full power. These magnetos also had a built in impulse delay switch allowing the armature to rotate faster than the crank to generate a hotter spark during starts. This impulse device helped to avoid backfires and possibly injuring the person cranking the engine. My father had already taught me how to safely crank a motor by first retarding the spark and keeping the thumb on the same side as your fingers. This jerked your hand away if the crank suddenly reversed from clockwise to counterclockwise rotation.

Safety was based on lessons learned and passed on from farmer to farmer. Learning to rebuild these tractors was an education in resourcefulness since cannibalizing parts from junked equipment was common practice.

From the time I was 10 years old, I also loved to build and fly model airplanes usually at the expense of doing my homework. My father took me to Roosevelt field often to see the marvelous aircraft of the Golden Age powered by Curtiss Wright and Pratt & Whitney reciprocating radial engines.

The War Years

Growing up, we were taught that World War I was the war to end all wars. However, World War II started only 20 years later and within 3 years, America was fighting in both Asia and Europe. Living within 25 miles of Republic and Grumman aircraft companies, I used to watch the P47 Thunderbolts and F4 Wildcats zoom overhead. It came as no surprise that my high school Civics class thesis was all about becoming an aeronautical engineer.

I joined the Army Air Force in 1944 with the promise of becoming a pilot. However, I had to wait until I was 18 to be called up and the war was already winding down. I ended up as in Enid, Oklahoma as a Link trainer instructor. The Link was a flight simulator designed to teach pilots how to navigate a two beam radio range and find the airfield in darkness or bad weather.

If I couldn't become a pilot, at least I would learn to "fly" the Link simulator. (Figure 2)



Fig. 2. Link at MAPS museum, Akron, Ohio

The Link cockpit had flight controls and instrumentation to receive the "A" and "N" radio signal beamed from a tower located at a prescribed map distance from the airfield.

By triangulating on these radio signals, a pilot could navigate the range and find the radio transmitting tower near the airfield in darkness. (Figure 3)



Fig. 3. Link flight control simulator cockpit

The Link instructor was in radio contact with the pilot while a "crab" moving on the range map recorded the flight path. (Figure 4)



Fig. 4. Link flight recorder and instructor

This training taught me to think about how people designed such clever devices and reinforced my resolve to become an engineer.

It was in March 1945 that I saw a jet aircraft fly overhead at Fort Dix leaving a long trail of smoke. I later learned it was the Lockheed P-80 "shooting star". I never saw another jet aircraft until long after my enlistment was over. Many years passed before I realized that the gas turbine jet engine would replace the familiar and revered reciprocating engines for both military and civil aircraft.

Getting an Education

After coming home at the end of 1946, I soon learned that the engineering schools in the Northeast were overcrowded with returning veterans. To qualify for these eastern schools, I had to take Trigonometry, and Advanced Algebra not offered in the high school I attended. I was overjoyed when I was accepted in the engineering school at Clarkson College which is now a University. I bought a slide rule and began a four year adventure learning the basic skills taught to engineering students. The engineering laboratory had a Junkers Jumo turbojet engine on display from World War II that powered the twin engine Messerschmitt 262 aircraft. I marveled at the axial compressor design and recall aluminum blades riveted to the disk rims. Many years later, I was unsuccessful in locating what happened to this engine.

It was a hot June day in 1951 when I graduated and I remember thinking "it's all downhill from now on". I didn't begin to realize this was only the beginning and that there would be many more hills to climb.

First Design Job - A Real Engine

I started my career with the General Electric Company but after two brief test assignments without design content, I joined the Fairchild Engine Division (formally Ranger) in Farmingdale, N.Y. Being short in manpower, I was immediately assigned to increase the power of the V-32, a ten horsepower air cooled auxiliary power unit on the B-29 aircraft. (Figure 5)

I used my Fordson tractor experience coupled with what I learned about internal combustion engine theory at Clarkson. I increased the intake and exhaust valve area by increasing the lift. Since the engine had overhead valves, I had to design depressions in the piston dome to avoid valve contact during maximum valve displacement.



Fig. 5. Fairchild V-32 Auxiliary Power Unit

Fortunately, Eric Delling, the famous steam car designer, worked nearby and helped me design the high lift cams and redesigned coil springs to prevent the valves bouncing on their seats. I was able to apply kinematics learned at Clarkson with the skills learned working on the Fordson tractors. I enjoyed a moment of euphoria when the engine test demonstrated 20% more power which was the performance goal.

My First Jet Engine

The Fairchild J44 turbojet was a single rotor engine with a mixed flow compressor at a pressure ratio of 3.3 driven by a single stage high pressure turbine. The engine powered the Ryan Firebee target drone, the Petrel missile and other applications. (Figure 6)

This engine produced 2450 lbs. of thrust with a thrust to weight ratio of 6.5 with a relatively short life consistent with target drone requirements. The J44 was later certified for manned aircraft by passing a 50 hour qualification test.



Fig. 6. Fairchild J44 Turbojet components

The components in [Figure 6](#) show the inlet housing, the mixed flow compressor rotor, the combustor, engine casing, HPT nozzle diaphragm, HPT rotor and exhaust nozzle. The original compressor rotor had a cast aluminum inducer followed by two forged magnesium axial impellers. After the engine experienced a compressor failure in service, “stretch marks” were observed in the web of the magnesium impellers. This is when I got my first rotor design job. My assignment was to design a one piece forged aluminum impeller to replace the two piece magnesium configuration. This required matching a disk to support a curved flowpath rim with integral blades.

Before computers, disk design analysis involved modeling the disk section into stacked radial ring segments and using a graphical approximation based on Stodola's differential equation solution. The length of time to design a disk using a “Sum and Difference” method depended heavily on the number of radial ring segments selected.

Fortunately, my supervisor was a brilliant designer and had me approximate the rim shell model as a rotating ring which I then matched to the disk web at the rim. The impeller was manufactured and successfully spin pit tested to 120% overspeed before the 50 hour qualification test. It's a great reward for engineers to see their creations work.

The next few years were an exciting adventure in design and analysis. My supervisor made us derive many of the equations used to solve analytical problems resulting in excellent training. This exposure resulted in several of us enrolling for an advanced degree with focus on theory of elasticity, theory of plates and shells and advanced courses in thermodynamics, mathematics, fluid flow and vibrations. The gas turbine is the world's most complex product and designers should strive to understand the theory used to develop the analytical models and tools.

A Marine Propulsion System

After World War II, the U.S. Navy became interested in Hydrogen Peroxide (H_2O_2) torpedoes and midget submarines. ([Figure 7](#))



Fig. 7. Fairchild X-1 Midget Submarine (Naval Academy, Annapolis, MD)

The X-1 displaced 36 tons submerged with a length of 50 feet and a crew of four. I was assigned the interesting challenge of designing the internal hull bulkheads and the non-conventional propulsion system.

The hull design involved ring stiffened bulkheads which were analyzed for inelastic buckling using empirical methods. The propulsion system consisted of a closed cycle four cylinder hybrid H_2O_2 / diesel engine with battery backup power. The H_2O_2 was catalytically decomposed into steam and oxygen used as the oxidant to burn the diesel fuel. The CO, CO_2 exhaust gases and condensed liquid H_2O were pumped overboard during submerged operation. The craft used the battery backup system for extreme stealth operation.

Transitioning to Computers

Before computers, engineers used what is commonly referred to as “hand calculations” for design analysis modeling. Both extensive theoretical knowledge and creativity were required to model complex designs using simplifying assumptions to achieve useful solutions. Extremes in boundary conditions were used to bracket the model behavior for structural configurations with non uniform thickness and complex geometry. The objective was to design a structure that would meet requirements using a wide range of boundary conditions. The degree of risk depended on the application and experience available.

For complex product design involving statically indeterminate structures, the use of strain energy methods invented by Menabrea and developed by Castigliano were used with simplified shape assumptions.

Graphical methods were used extensively to calculate the first lateral flexural frequency of airfoils and rotors for turbomachinery applications. These graphical methods were also used in aerodynamic calculations such as in the “method of characteristics” whereby partial differential equations are reduced to ordinary differential equations suitable for graphical integration.

During the early 1950's, the use of IBM computer punch cards used by finance groups were used to also program and “crunch” complex engineering solutions. More precise analysis of complex structural models was immediately recognized by early computer applications using the Prohl-Myklestad method to calculate rotor system and airfoil vibration modes.

Learning to Apply Analysis to Design

Both Fairchild and General Electric were awarded contracts to design competing axial flow engines with a challenging 10:1 thrust/weight ratio in the 2500 lb. thrust class. The Fairchild engine, the J83, differed from the J44 by incorporating a newly designed 7 stage axial compressor driven by a 2 stage turbine. I was assigned to design the first stage rotor blade of the seven stage compressor and the segmented turbine nozzle diaphragm. The famous aeroelastician Therodorsen was hired to determine the flutter

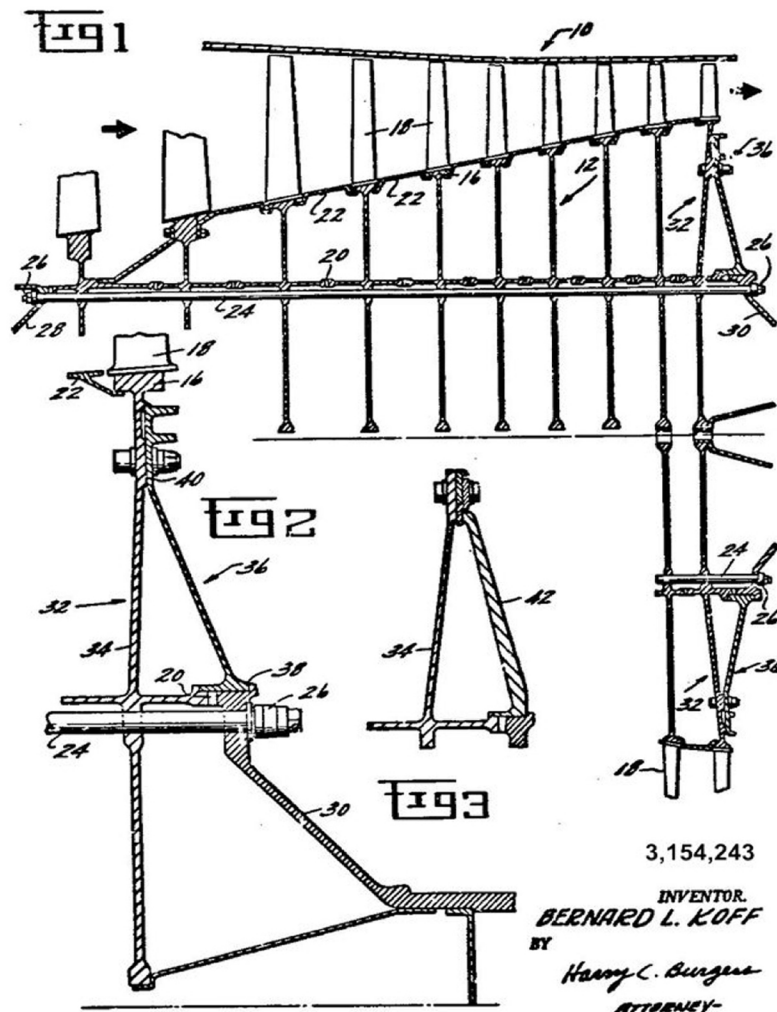


Figure 8. YJ93 compressor rotor schematic using titanium and A286 materials

margin and I was assigned to work for him performing calculations. Unfortunately, engine testing revealed that the single airfoil flutter theory (self excited vibration) was not applicable to the rotating cascade in an axial compressor.

Before computers, one of the simple methods to find the center of gravity of an airfoil section was to make a 10 to 20 X size cardboard model and “hang it up” in several positions against a plumb bob or vertical reference. The crossing vertical lines on the model defined the center of gravity of the section. This method was used extensively to create the stacking axis of the airfoil sections and resulted in excellent correlation with laborious moment of area methods and later computer solutions.

The analysis and design of the turbine nozzle using four welded vanes per segment was a challenge using simplified modeling, strain energy methods and simultaneous equations.

With a conservative thrust/weight ratio similar to the J44, the J83 engine was considerably below the goal of 10:1 and with typical development problems. The engine program was cancelled when the now famous General Electric J85 engine won the competition.

Changing Companies

I arrived at the General Electric Company in mid 1958 in time to be assigned to the YJ93 engine for the XB-70 supersonic bomber. Shortly after arriving, I was able to solve a compressor discharge seal failure that occurred during a test in the Lynn facility. The compressor rotor was a curvic coupling design with free rim spacers retained axially by having a coned rear disk that moved forward at the rim due to centrifugal force to provide axial clamping. However, during a rapid shutdown transient, this rear conical disk moved aft rubbing out the discharge seal. The solution for this compressor rig and engine problem resulted in my first patent. (Figure 8)

Within the drawing, Fig1 shows the aft 10 stages. Fig3 was the heavy cone “quick fix” for the rig compressor and Fig2 is the lightweight flight rotor design.

I was promoted to J93 compressor design supervisor, my first management position, for predicting, prior to the rig test, the discharge seal would fail during a shutdown transient.

Shortly afterward, the 12 stage compressor unexpectedly stalled on the engine operating line. Not only did the compressor stall, but the flexible short chord blades and vanes “clanged” together with substantial damage. All 12 stage short chord compressors returned from test with damaged airfoils.

This is when my group of mechanical design engineers was assigned to design a new “long chord” 11 stage compressor matching the current axial length to fit the engine. The new compressor was tested and the aerodynamicists got the pleasant surprise of getting a substantial increase in stall margin with the longer airfoil chords. The year of 1959 was when GE discovered and demonstrated that:

$$\text{Clearance} / \text{airfoil length} = \text{efficiency}$$

But,

$$\text{Clearance} / \text{airfoil chord} = \text{stall margin}$$

Also, the concept of considering the many more operability factors shown in [Figure 9](#), became a critical criteria of the design process.¹

Other problems surfaced during development.

The compressor experienced a first stage blade failure at Mach 2 during heated inlet testing. An intensive investigation revealed that the blade failure was caused by self excited vibration, more commonly known as flutter. Several blade redesigns were made including the use of friction pins connecting adjacent airfoils at midspan to provide damping.

During pre-PFRT (preliminary flight rating test), the friction pins supported by holes in the airfoil released into the flowpath causing major damage. Fortunately, before this incident, my rotor blade designer returned from a vendor site with a scrapped P&W JT3D blade with a partially machined midspan shroud. We immediately manufactured three sets of first stage blades with midspan shrouds which were ready for installation to pass PFRT.² ([Figure 10](#))

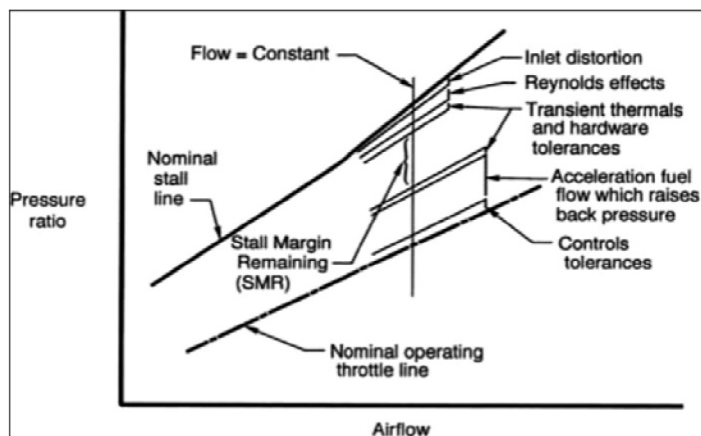


Figure 9. Factors influencing compressor stall in engine systems



Figure 10. YJ93 first stage titanium compressor blades with midspan shrouds (1960)

I was severely criticized for copying a P&W design and the department manager prohibited their use until the airfoil friction pins failed.

The JT3D midspan design is still being used worldwide for moderate aspect ratio blading to absorb and suppress vibration caused by flutter.

The YJ93 experience provided a giant step forward in the process of learning to apply analysis and creativity. The smooth spool curvic coupling rotor had 21 hollow tiebolts, blades and disks made of titanium and A286, a double stage discharge seal using labyrinth teeth with honeycomb seals and rabbit supported rim spacers. The compressor stator had both front and rear variable vanes. The rear variable vanes were opened above Mach 2 to reduce the overall pressure ratio, reduce the high discharge temperature and increase airflow.³ ([Figure 11](#))

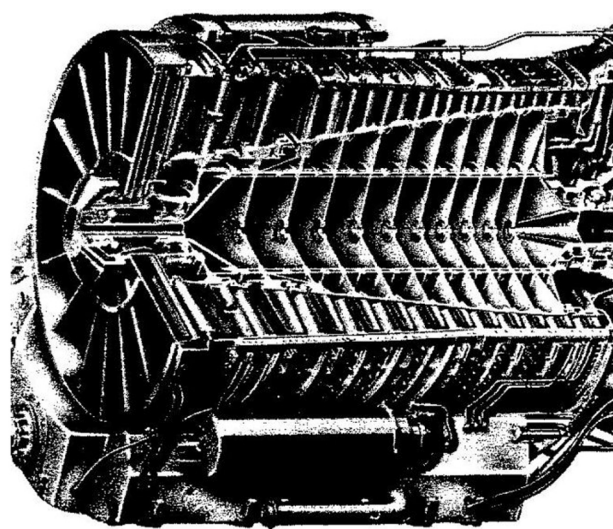


Figure 11. GE YJ93 Compressor, 11 stages, 262 lb/sec flow, 8.75 pressure ratio with front and rear variable stators