5 Crankshaft Development

One of the things that made the original Pratt & Whitney "Wasp" so successful in 1926 when it first passed its type test was the ability to make its power at a higher RPM and a lighter weight than its competition. Key to this accomplishment was the use of a one-piece master rod and two-piece crankshaft. Though two-piece crankshafts had been built before, George Mead and Andy Willgoos chose a new construction consisting of a split crankpin splined to its mating crankpin, the whole assembly being held together with a bolt through the center of the crankpin. See Figure 5.1.

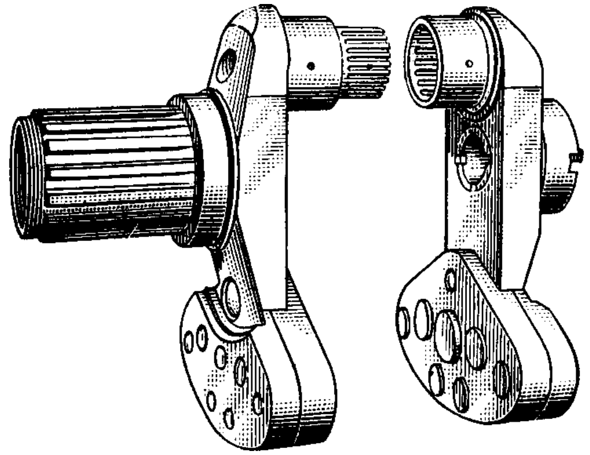

Figure 5.1 "Wasp" Crankshaft **(Pratt & Whitney)**

This construction was used in many, but not all, Pratt & Whitney designs preceding the R-2800. It is therefore no surprise that the designers chose this same type of construction for two-throw R-2800 crankshaft. The original R-2800 crankshaft compensated for the weight of the master rod and link rods in the usual fashion, by providing a counterweight that balanced all of the rotating mass and one-half of the reciprocating mass. Initially, no vibration dampers of any kind were provided. It is unclear whether this was wistful thinking on the part of the designers, or merely acknowledgement that no one could predict the vibration behavior anyway, so they may as well start testing to uncover the problems as early as possible. One thing the designers did consider was placement of the master rods as close at possible to 90 degrees to one another so that second-order inertia torques could cancel as nearly as possible, reducing 2X torsional excitation of the crankshaft.

George E. Meloy was heavily involved in R-2800 crankshaft development almost from the start. One of his first jobs at Pratt & Whitney was to write a report on the history of R-2800 development, which included many details on the successes and failures of the crankshaft. Meloy was later responsible for sorting out problems with the "C" engine crankshaft and getting it into successful production in the Kansas City, Missouri plant. Some of the people who worked for Meloy remember him for being the only person they know who could walk into a test cell and not get oil on his clean white shirt.

Meloy was born in Chicago in 1916, but at the age of four moved east to New York. He eventually settled in Teaneck, New Jersey where he graduated from Teaneck High School. Meloy received a Bachelor of Aeronautical Engineering from New York University. Despite the scarcity of jobs brought about by the Depression, Meloy started work at Pratt & Whitney one week after graduation in 1938. Initially a test engineer, Meloy advanced rapidly through project engineering and finally into management. While his real love was in development, like many capable technical people, he had the management role forced upon him. However, he did not despair. Says Meloy, "Every moment spent at Pratt, to me, was worth while. I didn't watch the clock, didn't have to. During the war years, we worked 54-hour weeks. There were no perks back in that time, understandably. We were just happy to do it. It gave us a feeling we were doing something worthwhile for the defense of the nation."

Connecting Rod Evolution

The first one-piece master rod assembly featured a locked silver-plated bearing and locked knuckle pins. A silver-plated flange on the forward face of the master rod bearing carried thrust loads on the master rod. This design was discarded because of weaknesses that became apparent during testing. By strengthening portions of the master rod and link rods that were highly stressed, as well as increasing the fillets and radii at stress concentration points, master and link rod structural failures were eliminated. Aiding this process was moving knuckle pin oil delivery passages to the knuckle pin retaining plates.

Much of the master rod development was done using brittle lacquers. These coatings were the only instrumentation available at that time for internal engine parts. Brittle lacquers have the characteristic of cracking when the material to which they have been applied flexes. By analyzing the concentration and orientation of cracks in the lacquers, highly stressed engine components could be improved by adding metal in the right places

Master rod bearing failures prompted a series of experiments into bearing construction and materials. The original copper-bronze and bronze bearings were replaced with silver-lead bearings in April of 1938, eliminating the material problems. The question of how to retain the bearings got more attention. These were originally a press-fit. Use of set screws to lock the bearings was tried but not successful.

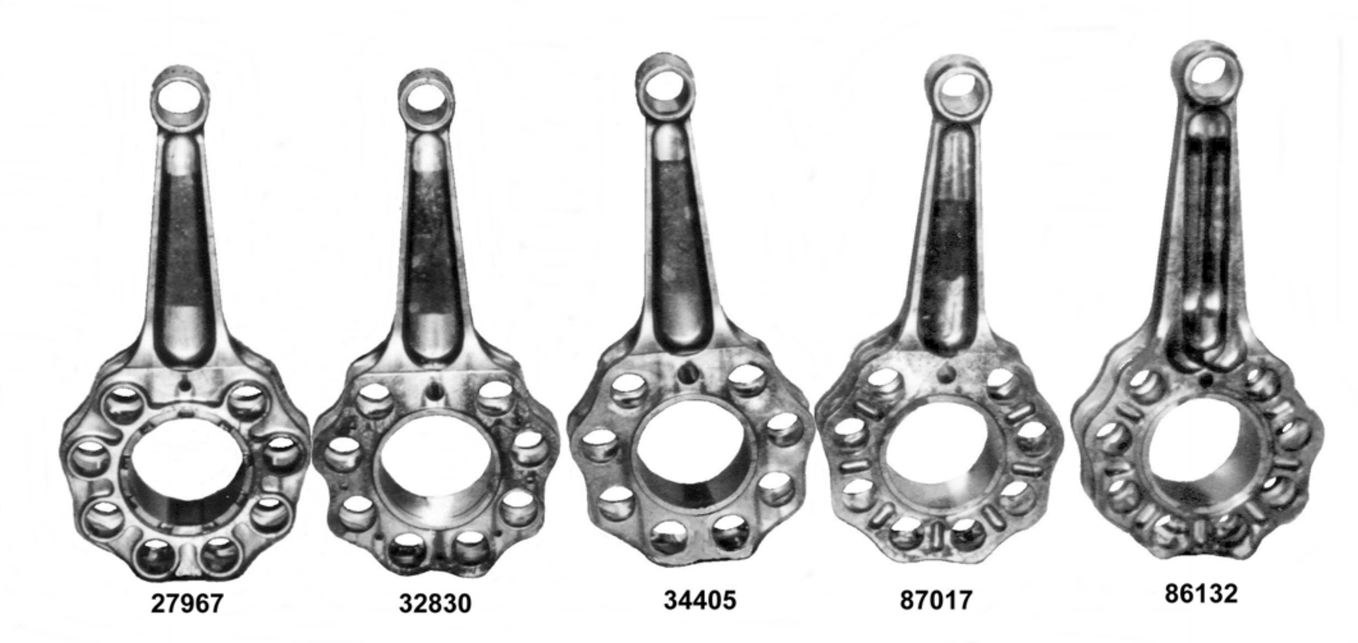

Figure 5.2 Master Rod Evolution **(Author)**

Neither was a floating bearing with silver-lead both inside and outside and a floating bronze thrust collar. Another floating bearing design with large aluminum plates fastened to the sides of the master rod was rejected because of metal transfer on the mating faces. Finally, a successful locked-bearing design with floating knuckle pins was tested in October of 1938. In order to reduce oil flow to the power section, master rod bearing clearances were reduced by 0.004”.[1]As engine power and maximum RPM continued to increase, connecting rod design evolved to meet the new challenge.

Figure 5.2 shows the evolution of R-2800 master rods. The two left-most rods, P/N 27967 and P/N 32830 are early experimental designs that never saw production. The center rod, P/N 34405 was used in the “A” and “B” series of engines. The fourth one, P/N 87017, was used in the “C” series of engines. The one on the right, P/N 86132, was used in early “E”, “CA”, “CB”, and “CE” series engines. Compare the sharp edges and tight radii on the early rods with the generous fillets and large radii of the later ones. Note the progressively larger cross section of the rods, and the center rib in the web of the later design. Extremely high quality of fit and finish is evident in all the examples.

Crankshaft Evolution

Early experience with the initial crankshaft design was problematical. Almost immediately, spiral fractures on the front crankpin began causing crankshaft failures. This was first blamed on master rod bearing seizures, but crankshaft failures continued to occur even after the bearing problems were solved. On August 8, 1938, a failure on engine X-79 after just 41 hours of operation forced design changes. These included revisions in the oil distribution and changes to the rear crankshaft gear locking provisions. It was during this same period that torsional vibration testing had indicated the need for 4.5X torsional vibration dampers which were then included in the rear counterweight.

Continuing problems with the spline that joined the R-2800 crankpins had resulted in several redesigns. This included moving the joint to the crankpin center from its previous off-center position, replacement of the machined spline with a splined plug, and hardening of the mating surfaces. In all cases, the changes failed to eliminate galling of the crankpin mating surfaces and spline faces.

These efforts were further hampered by occasional crankshaft failures resulting from the fact they were hand-forged. Whereas later production crankshafts would be die forged, the crankshaft design was not yet finalized, and the price of forging dies prohibited their use for experimental crankshafts. Problems with hand forging due to inclusions and poor grain structure were well documented, and led to many crankshaft failures.[2]

Dana Waring, one of the test engineers who made a career at Pratt & Whitney, remembers a spectacular crankshaft failure. Waring was observing an engine running at full power in the test cell. It was outfitted with a metal flight propeller that, in conjunction with the short exhaust stacks, was making a huge amount of noise. In the blink of an eye, and with a loud bang, the engine rotated 180 degrees in its test stand fixture, tore loose from its mounts and came to rest on the test cell floor, leaking oil and smoking. In the mean time, the propeller had sheared off and flown forward to the front of the test cell, knocking a dent in the concrete wall. The propeller hovered there for a few revolutions until it lost some momentum, and then slid to the floor, still rotating. When the propeller blades began hitting the floor, the entire propeller began walking around the forward end of the test cell until it used up its remaining momentum and came to rest. Dana Waring was thereafter very reluctant to enter the test cell while an engine was running.

Despite difficulties with crankshaft development, it was this crankshaft design that was used in the R-2800 “A” and “B” series engines that saw the majority of the action and contributed so much to the winning of World War II. See Figure 5.3.

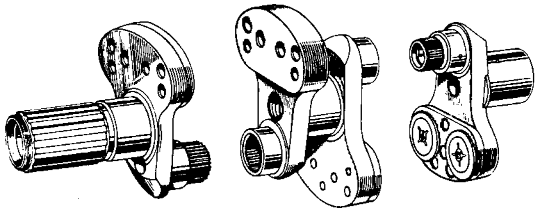

Figure 5.3 "A/B" series Crankshaft (Pratt & Whitney)

The higher horsepower and redline RPM of the “C” engine required major changes in crankshaft design. The engineers followed two different threads of crankshaft development. The first continued to refine the splined crankpin connection while the second pursued a clamp-type crankshaft.

In late February and early March of 1939, a new crankshaft design with two counterweights instead of four was tested. This design offered a considerable weight savings of over 32 pounds, and also facilitated elimination of the two-piece crankcase center section that had been used on the “A” and “B” models[3]. The initial two-counterweight crankshaft was made from an old four-counterweight crankshaft, and did not have 4.5X torsional vibration dampers.[4] This crankshaft, an old design that was hand-forged, failed through the rear crankpin after it had accumulated a total time of 453.2 hours, and 151 hours after rework to the two-counterweight configuration. Metallurgical examination revealed poor grain flow and structure and recommended strategies to prevent such failures in the future.[5]

In addition to problems with material properties, failure of the two-counterweight splined crankshafts, was attributed to the bending vibration in the crankshaft. This led to a design in which the effective mass of the rear counterweight was reduced in the fore-aft direction by installation of two cylindrical plugs in the counterweight that were free to slide fore-aft along their axes. Torsional and linear vibration were not measurably different from the earlier two-counterweight spline-joined crankshafts without the loose plugs.[6]

Frequencies of resonance in bending were measured using some clever instrumentation produced by Gorton and Crocker. This consisted of a horizontal linear vibration pickup mounted on the crankshaft axis. An adapter tube screwed to the rear crankshaft journal extended through the accessory drive shaft to the exterior of the engine. Rotation between the adapter shaft and vibration pickup was via a preloaded double-row ball bearing. A second horizontal vibration pickup mounted on the vacuum pump adapter pad external to the engine sensed overall engine vibration. Comparison of signals from the two pickups allowed measurement of fore-aft motion of the crankshaft. This motion could then be related to the bending vibration of the crankshaft. These bending vibration tests indicated that the loose plugs in the rear counterweight were effective in eliminating 4.5X bending vibration that was believed to have contributed to the breakage of the earlier two-counterweight crankshaft design.[7]

Clamp-type Crankshaft

One solution to the weakness of the splined crankshaft was a clamp-type crankshaft. This took the form of a two-counterweight crankshaft without 4.5X torsional vibration dampers that received considerable attention and testing from May through October of 1939. This crankshaft design had slightly better 4.5X propeller blade tip stress characteristics than the four-counterweight crankshaft, but otherwise had identical vibration characteristics with the two-counterweight splined-crankpin crankshaft.[8] But it was also harder to assemble, requiring special alignment fixtures and assembly techniques, and prone to slippage. Considerable experimentation went into finding the correct amount of clamp bolt stretch. Each experiment involved engine teardown, inspection, and reassembly. The frequent tightening of the clamp bolt caused galling of the clamp surfaces and necessitated re-drilling of the cotter pin hole in the clamp bolt with each assembly.[9]

Refinement of the clamp-type crankshaft continued. Dynamic counterweights were added, along with other improvements. Planners intended this type of crankshaft for the production "C" engine to be built in Kansas City, Missouri. Much of the experimental development of the "C" engine, which began on September 1, 1940, was done with the clamp-type crankshaft.[10] But this crankshaft design never saw production. See Figure 5.4.

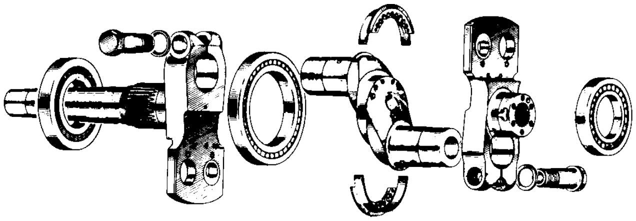

Figure 5.4 Clamp-type Crankshaft Representative of Those Tested By Pratt & Whitney (Navy)

Face-splined Crankshaft

Instead, a face-splined crankshaft construction was developed and used in the "C" and all subsequent R-2800 engines. See Figure 5.5.

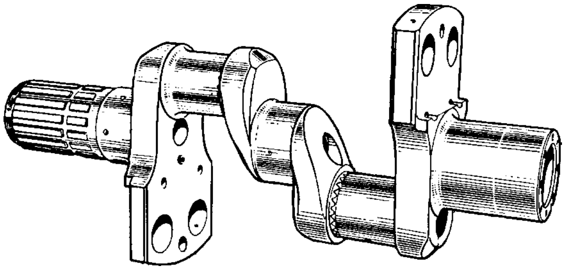

Figure 5.5 "C" series Crankshaft (Pratt & Whitney)

It is the opinion of the author, and this opinion is shared by retired Pratt & Whitney engineers Elton Sceggel[11] and Gordon Beckwith[12], that improvements in gear-cutting technology at the Gleason Works of Rochester, N.Y. made possible the machining of complex involute splines necessary for this new joint. See Figure 5.6.

The face-splined crankshaft is first mentioned in a report on the bending behavior of various crankshaft joints. In this report, six joint designs were tested: the traditional internal spline; the clamp-type; the face splined with an internal tension bolt torqued to a stretch of 0.0018"; a hollow one-piece pin (to simulate a one-piece crankshaft; a face-splined with plug; and a face-splined with an internal tension bolt stretched to 0.0068".

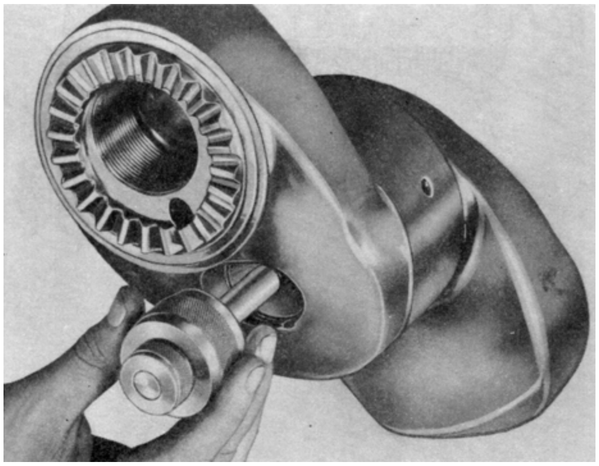

Figure 5.6 Detail of Face Splines (Pratt & Whitney)

The results are presented in Figure 5.7, which strongly supports the argument that the face-splined construction with proper tension bolt torque is far superior to other designs.[13]

The face-splined crankshaft construction was not without its development troubles. A large bolt centered in each crankpin held the face splines in close contact. It took considerable experimentation and cost George Meloy a lot of sleep before suitable locking pins for this bolt were produced.[14]

By October 29, 1942, the first examples of the face-splined two-counterweight cranks with 4.5X bifilar dampers on the rear counterweight were undergoing torsional and linear vibration testing. It is noteworthy that in this test, master rods were installed twenty degrees apart in cylinders 8 and 9. This arrangement was ideal for eliminating 1X torsional vibration at the expense of 2X torsional vibration.[15] Later addition of a 2X bifilar torsional vibration damper to the front counterweight eliminated the 2X torsional vibration problem inherent to this master rod orientation.

While the crankshaft would undergo continued improvement during its service life, these changes were minor, consisting of things like silver-plating the face spline mating surfaces and use of lighter weight bifilar damper construction. The face-splined joint concept proved itself in service and remains in use in R-2800 "C" and later engines in use today.

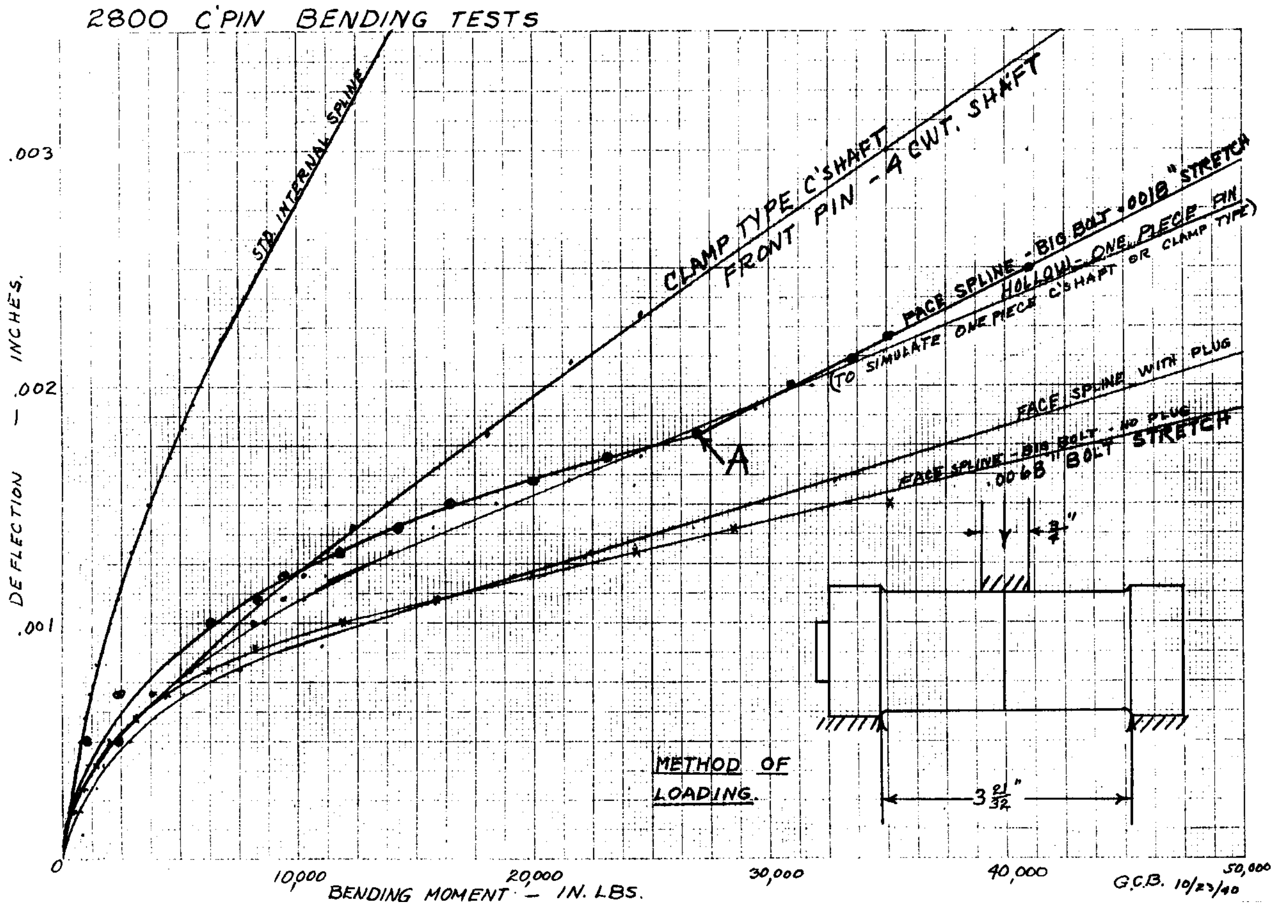

Figure 5.7 Crankshaft Bending Studies **(Pratt & Whitney)**

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[1] George E. Meloy, "Report on History of R-2800 Engine Development", (PWA Report No. PWA-192, May 30, 1939), 8.

[2] Ibid., 9.

[3] The two-piece center crankcase had always been problematical. It required additional machining operations in production, and was subject to fretting between the case halves. A one-piece casting would eliminate these difficulties.

[4] R. E. Gorton and A. R. Crocker, "Torsional Vibration of the R-2800 Engine with Two-Counterweight Crankshaft using 6159-0 Hydromatic Propeller With and Without Paddle Dampers", *SMR No. 547* (March 31, 1939).

[5] W. J. Closs, "First R-2800 Two Counterweight Crankshaft", *SMR No. 617* (November 21, 1939).

[6] R. E. Gorton and A. R. Crocker, "Linear and Torsional Vibration of R-2800 Engine X-83 with Loose Crankshaft Counterweight Plugs Operating in the Horizontal Intake 18' Test House", *SMR No. 619* (November 22, 1939).

[7] R. E. Gorton and A. R. Crocker, "Vibration in Bending of the Two-Counterweight R-2800 Crankshaft with Loose Plugs in Rear Counterweight", *SMR No. 622* (December 5, 1939).

[8] R. E. Gorton and A. R. Crocker, "Crankshaft Torsional Vibration and Linear Vibration of the R-2800 Engine with Clamp-Type Crankshaft and Hydromatic 6159-0 Propeller", *SMR No. 569* (June 27, 1939).

[9] W. J. Closs, "R-2800, Two Counterweight, Clamp Type Crankshaft", *SMR No. 609* (October 31, 1939).

[10] "R-2800 Development", (Internal P&W working paper, author unknown, some pages marked "F.W.P. 6-22-45).

[11] Elton Sceggel, telephone interview by the author, (Huntsville, AL, March 22, 1999).

[12] Gordon Beckwith, telephone interview by the author, (Huntsville, AL, March 22, 1999).

[13] G. C. Barnes, "2800 Crankpin Bending Tests", *SMR No. 686* (October 29, 1940).

[14] Beckwith.

[15] R. W Pratt, "Crankshaft Torsional and Engine Linear Vibration of the R-2800-37 Engine X-88 with Two-Counterweight, Face-Splined Crankshaft, a 4 1/2X Bifilar Damper on Each Counterweight, and Master Rods in Cylinders #8 and #9", *SMR No. 871* (November 27, 1942).