



2013

CLIFF GARRETT TURBOMACHINERY ENGINEERING AWARD

2014-01-1647

The Radial Turbine for Small Turbocharger Applications: Evolution and Analytical Methods for Twin- Entry Turbine Turbochargers

Dr. Norbert A. Schorn
Ford Motor Company

Presented at:
SAE 2014 World Congress
Detroit, MI
April 8, 2014

CLIFF GARRETT TURBOMACHINERY ENGINEERING AWARD

Description

This award promotes engineering developments and the presentation of SAE papers on turbomachinery and/or developments that enable or advance the use of turbomachinery. The award honors Cliff Garrett and the inspiration he provided to engineers by his example, support, encouragement, and many contributions as an aerospace pioneer. To perpetuate recognition of Mr. Garrett's achievements and dedication as an aerospace pioneer, SAE administers an annual lecture by a distinguished authority in the engineering of turbomachinery and/or engineering related to creating, enabling, or advancing applications of turbomachinery in power systems, on-highway, off-highway, aircraft, and/or spacecraft uses.

The Award

This award, established in 1984, is administered by the Garrett Award Selection Committee and consists of a framed certificate, a commemorative gift and an honorarium. The award is made possible by a contribution from the Garrett Corporation (now a division of Honeywell).

The lecture honors the memory of Cliff Garrett, an Aircraft pioneer and entrepreneur. Under Cliff's leadership, Garrett was the first to build small auxiliary power gas turbines. One APU series that Cliff's engineers started in the 1950's is still in production today. This is the 85 series, a product that has outlived the company that bore Cliff's name.

Although Garrett ceased to exist as a corporation in late 1987, individual Garrett divisions thrived under the AlliedSignal Aerospace banner until its acquisition by Honeywell. These divisions include the Phoenix-based Garrett Auxiliary Power Division and the Garrett Engine Division, which produce APUs and propulsion engines respectively.

Cliff had an overriding determination to see his company established as a propulsion engine supplier. This was just beginning to happen when he died in 1963. Cliff's successor made that goal a reality. Cliff had an intensity and drive that were unequaled. He built Garrett from ground zero to a billion dollar company. Growth from within was achieved by product engineering innovation, as well as by a strong and dedicated sales team. Cliff represented a personalized, hands-on leadership style that was just right for his time and his company. We will always need leaders of his spirit and vision.

The Garrett Award Selection Committee welcomes nominations for future lectures and suggestions for subject matter related to the basic objective of the program. Nominations and suggestions may be emailed to awards@sae.org. For additional award information, please visit <http://awards.sae.org/garrett/>.

AWARD RECIPIENTS

2013 Dr. Norbert A. Schorn

2012 David K. Winstanley

2011 Bernard L. Koff

2010 None

2009 Dr. James W. Fuller

2008 Dr. David Japikse

2007 Vern E. Brooks

2006 V. Ganesan

2005 John J. Adamczyk

2004 Dr. Ramesh Rajagopalan

2003 Steven D. Arnold

2002 Vincent A. Pedotto

2001 Carl Schopfer

2000 Barry Weinstein

1999 Robert Lorimer

1998 Eugene D. Jackson III

1997 J. P. (Jean-Paul) Frignac

1996 None

1995 Heinz F. Moellmann

1994 Frank C. Gillette, Jr.

1993 John Acurio

1992 M. L. (Joe) Stangeland

1991 John L. Mason

1990 John D. Denton

1989 Calvin L. Ball

1988 F. Blake Wallace

1987 Colin Rodgers

1986 Arthur J. Wennerstrom

1985 Frank E. Pickering

1984 David P. Kenny

CLIFF GARRETT TURBOMACHINERY ENGINEERING AWARD



2013 Recipient

Dr. Norbert A. Schorn
Ford Motor Company

Dr. Norbert Schorn studied mechanical engineering at the RWTH Aachen University. From 1978 onwards, still as a student, he got involved in experimental studies on a hot gas stand for twin flow turbocharger turbines and on engine test benches for turbocharged Diesel engines at the institute of Prof. Dr. Franz Pischinger. He continued his work on turbochargers and turbocharged engines after his diploma degree in 1981, and finally received his doctorate from the RWTH Aachen University with summa cum laude.

Dr. Schorn continued his association with turbochargers and combustion engines during his professional life at Deutz AG in Cologne, at MTU in Friedrichshafen and later on at FEV in Aachen, Germany. In the year 2000, he joined the Ford Research Center in Aachen and soon became the global top technical expert for boosting technologies for Ford Motor Company.

During his professional life, Dr. Schorn collected wide experience and superior understanding of turbocharger and supercharger technologies and the interaction between different boosting systems and the internal combustion engine. This refers to very different types and sizes of engines and engine applications from small gasoline engines, to light duty and commercial Diesel engines for HD and off-road vehicles, up to large bore engines for marine and power station systems.

His passion for boosting technology in general motivated him to write a very comprehensive compound of the historic development of superchargers and supercharging of internal combustion engines. This document includes a description and analysis of most derivatives of mechanical driven superchargers from 1900 on.

Dr. Schorn authored numerous papers that focused on engine cycle simulation and boosting technologies. His continued interest was and still is to further improve the interaction of the internal combustion engine with the turbo machine. Some important examples to label are papers about the Atkinson cycle for large bore Diesel engines, about regulated 2-stage turbocharger systems and also about parallel sequential turbocharging systems. He also drove for extended mapping of turbochargers, low turbocharger speed measurement technology to improve the launch performance and turbocharger friction analysis. He always continued to foster a close cooperation between engine and turbocharger manufacturers. Moreover, Dr. Schorn lectured at the RWTH Aachen University and the Stuttgart University about boosting of the internal combustion engine.

He is currently an age indexed part-time employee of Ford Motor Company and a technical adviser for FEV.

The Radial Turbine for Small Turbocharger Applications: Evolution and Analytical Methods for Twin-Entry Turbine Turbochargers

Norbert A. Schorn

ABSTRACT

In 1917, French Prof. Rateau built and operated the first turbocharger. He used an axial turbine because of existing experience from the steam turbine to drive a centrifugal compressor. From then on the axial turbine was improved regarding temperature capability and performance and is still the first choice for larger turbochargers today. From the beginning, multi-entry turbines, as discussed in the patent of Büchi in 1925, were applied to make use of the pulse effect and, thus, to improve the engine performance at low speed and during transient operation. Between 1936 and 1945, the radial turbine for gaseous substances was proposed and finally implemented for smaller units, mainly because of lower complexity and cost. From the beginning, variable nozzle turbines were designed and built but without entering mass production. Up until 1963, multi entry turbine housings for radial turbines, like the axial turbine variants, were solely segment controlled. The twin entry turbine patent for radial turbines was filed by Garrett in August 1963 and the turbochargers went into production the same year at Caterpillar. Today there is an increasing share of 4 cylinder gasoline engines that make use of the twin entry turbine feature. This paper proposes a gas stand analysis process to measure the behavior of these turbines under unequal flow conditions in an extended pressure ratio operating range. A special turbocharger test rig for low turbocharger speed was set up in addition to a friction test rig to extend the turbine map for part load and transient optimization and simulation. Friction measurements as function of speed and thrust load were performed to separate mechanical from aerodynamic performance. A method to describe and analyze twin flow turbines is presented. In addition, backflow in the turbine was measured. These methods should help to improve the turbocharger behavior and to achieve refined turbocharger-engine interaction.

CITATION: Schorn, N., "The Radial Turbine for Small Turbocharger Applications: Evolution and Analytical Methods for Twin-Entry Turbine Turbochargers," *SAE Int. J. Engines* 7(3):2014, doi:10.4271/2014-01-1647.

INTRODUCTION AND EARLY TURBOCHARGERS

Everybody who deals with turbocharging knows the name of the Swiss engineer Alfred Büchi who graduated in 1903 at the Swiss Institute of Technology in Zürich.

In 1904, Büchi was hired to lead the design and testing of a gas turbine for the diesel engine manufacturer Carels Freres in Ghent, Belgium. His work resulted in the first patent of 1905, in which he described how a diesel engine linked to an exhaust turbine and to a compressor could increase the power output and the overall efficiency of the engine.

Since 1911, experiments performed by Sulzer in Switzerland provided important information about absolute pressure levels and scavenging pressure. The scavenging patent of 1915 describes how a suitable design of the valve overlap allows the cylinder to be purged to increase engine performance while at the same time limiting the exhaust gas temperature to acceptable levels.

Later, in 1925, Büchi applied for a pressure wave (or pulse-charging) patent. This was realized by using individual exhaust manifolds and combining the cylinders with ignition intervals of more than 240° crank angle. The different exhaust pipes required one or more turbines [1]. In order to leverage the benefits of improved "scavenging", i.e. more fresh air in the cylinder and the limitation of the exhaust temperature, multi-entry turbines became a necessity.

These basic patents attracted worldwide attention.

Since 1894, French Professor Auguste Rateau was one of the pioneers of the steam turbine development. His name also stands for the multi-stage impulse steam turbine. Rateau was probably inspired by the Büchi publications and in 1916 he filed a patent, which described a compressor driven by an axial impulse exhaust turbine. His design focussed on the application in turbocharged aircraft engines. It featured assembled, single turbine blades and an outer journal bearings system since ball bearings were not yet available. The axial thrust of the rotors created bearing problems. The turbine was made of tungsten-steel and allowed peak temperatures of

approximately 700 ° C. The turbocharger went into production towards the end of World War I in 1917. While the reliability was disappointing, the turbocharger of Rateau may go down in history as the first free running turbocharger.

GENERAL ELECTRIC

Almost simultaneously to Rateau's turbocharger flight tests, the U.S. National Advisory Committee for Aeronautics, namely Dr. William F. Durand, approached General Electric concerning war-related rapid development of a turbocharger. They had obtained intelligence about Rateaus's plan and intended to do research in the United States. General Electric had a high interest in the development of gas turbines and began the design of centrifugal compressors in 1903.

Under the lead of Dr. Sanford Moss, GE ran first high altitude tests on Pikes Peak (4301m) as early as 1918. Manually operated initially, the turbine waste gate was later controlled by a servo-valve or electric actuator. The axial turbine was intensively air-cooled. Forged turbine blades made of chrome steel were subsequently replaced by fully machined ones. The ball bearings allowed a vertical arrangement of the turbocharger. The reliability of the early turbochargers was limited to only a few flights primarily due to material defects and bearing failures.

In the early 1920's, the research of high temperature material at the Haynes Stellite Company in the United States resulted in nickel-molybdenum alloys, which showed a significantly increased resistance to high temperatures. At the end of the decade, alloys with chrome components had been developed, now enabling lifetimes of several hundred hours at 820 ° C.

Sanford Moss retired in 1938, but with the beginning of the 2nd World War turbocharging for airplanes got a high priority in the USA. Sanford Moss was again involved in this development and in 1940 the turbocharger was installed into the B17 bomber which reached a safe altitude of approximately 10.600 meters. The United States were the only country in the 2nd World War to use the turbo-supercharger in high volume.

Haynes Stellite 21 and 31 was used for the turbine blades. With approximately 25 million turbine blades, Haynes delivered approx. 70% of the required volume. Initially, forged blades were produced with subsequent mechanical processing, but soon replaced by the awake lost wax method developed in the U.S.. The U.S. had a technological lead over Europe in this area. It is estimated that approximately 300,000 turbine wheels were built during that time.

One month after the attack on Pearl Harbor on December 7th, 1941, the U.S. Air Force contacted Ford Motor Company to negotiate the production of the GE turbo-supercharger as General Electric's capacities were fully used. Eight months later, in September 1942, production began at Ford in the River Rouge plant. All required laboratories were prepared for test runs. Ford introduced several important changes concerning

casting technology as well as the welding processes to reduce the manufacturing effort and costs. A total of 52.281 turbochargers were built at Ford until the contract ended in November 1944 /2/, Fig. 1.

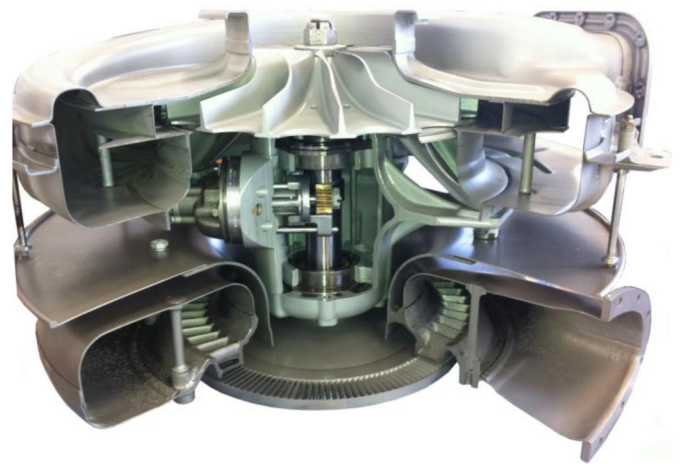
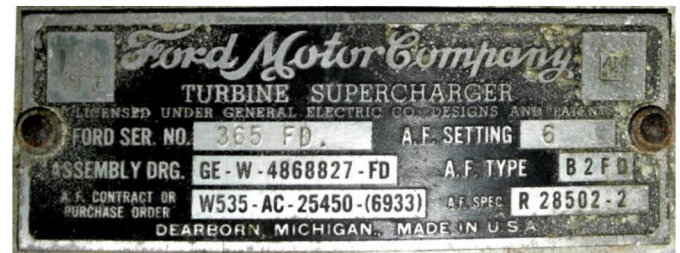


Fig. 1. Ford Turbosupercharger, 1942-1944

DVL

In 1934, at the age of 28, Dr.-Ing Werner Theodor von der Nüll became the head of the Institute for Turbomachinery at the German Research Institute for Aeronautics (DVL) in Berlin. He was appointed Research Professor in 1940 and became the DVL's specialist for supercharging and turbocharging of internal combustion engines. He introduced the pre-swirl unit for the mechanically driven compressors of airplane engines. With the application of hollow turbine blades, he enabled the turbine to operate at high exhaust gas temperatures. Almost all turbochargers at that time featured the axial turbine design. Von der Nüll recognized the advantages of the radial turbine design for smaller exhaust turbochargers, namely low specific speed, corresponding to high energy content at low mass flow. The overall high simplicity and the advantages concerning bearing system and gas guidance lead him to run test on a radial compressor of a Daimler Benz aircraft engine in 1936. This mechanically driven compressor) was measured at the DVL with the direction of rotation adapted to function as a turbine. Encouraging levels of efficiencies above 80% were measured /3,4/, Fig. 2.

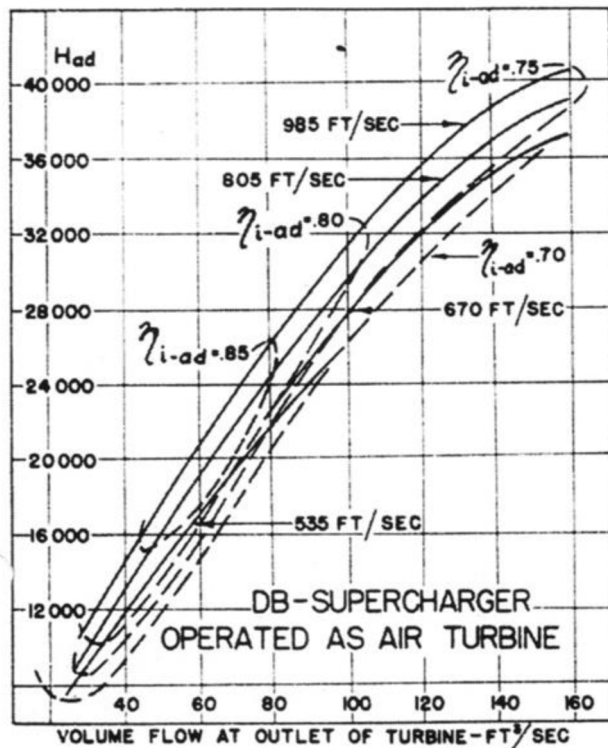
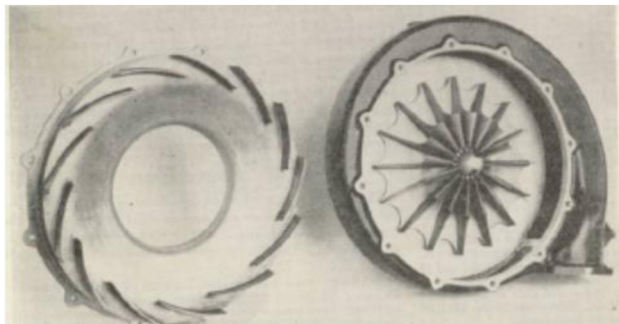


Fig. 2. DB-Supercharger, shown above, operated as an air turbine. /3/

In 1943, a young engineer by the name of Otto Erich Balje received the assignment to perform theoretical and experimental investigations of radial turbines. The achievements are documented in his PhD thesis as acknowledged by the Technical University Munich in 1944. His supervisors were Prof. Dr. Werner T.v.d. Nüll and Dr. Eugen Knörnschild, who were both employed at DVL at the time while later becoming affiliated with Garrett. Eugen Knörnschild reported already in 1943 about the common work on a small radial turbine with a variable geometry by movable vanes (VNT) /6/. The radial turbine enables a simple realization of the movable vanes because of its parallel walls in front of the wheel inlet/4,5,6/, Fig. 3.

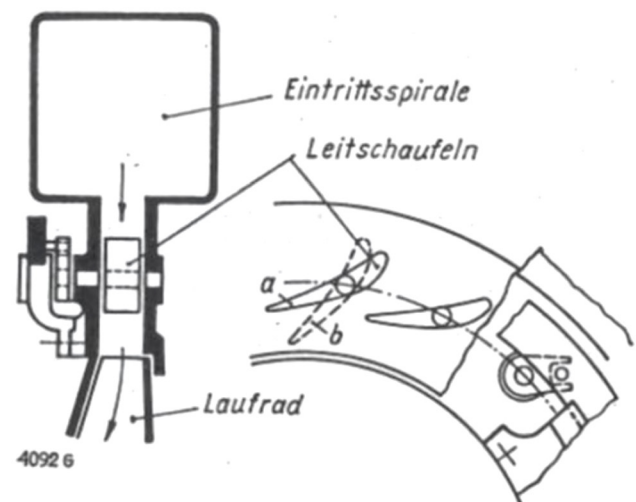
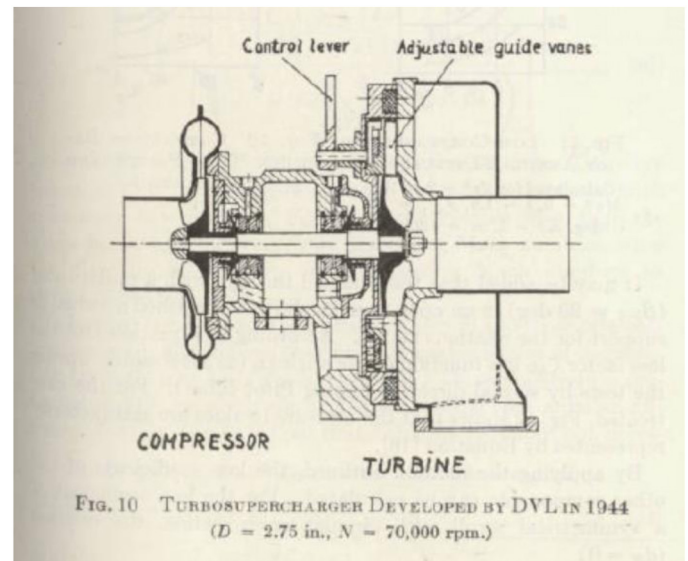


Fig. 3. VNT developed at DVL 1944 /5, 6/

W.T.v. d. Nüll wrote later that this work on VNT turbines had started already shortly after the "reversed tests" of 1936. Already at that time it was recognized that radial turbines don't have to use an expensive fixed nozzle ring. O.E. Balje described the advantages and disadvantages of the radial turbine design in his work and made a reference to the mixed flow turbine. O.E. Balje was later recognized because for his book "Turbomachines: A Guide to Design, Selection and Theory" /7/. He also taught evening classes in the analytical design of small turbomachines at the University of California in Los Angeles in the early 1950s/8/.

At the end of the 1940's, W.T.v.d. Nüll (now Garrett AiResearch) and O.E. Balje had become strong advocates of the radial turbine type in the USA /3,4,5/, particularly because of the potential for a low cost VNT.

WMF-EBERSPÄCHER-KKK(BORG WARNER)

At the end of WWII, a small group of BMW aircraft engine engineers played a crucial role in the development of the turbo-supercharger of today's compact, cost efficient design: Dr. Alfred Müller and Gustav Zellbeck were both involved in the development of the BMW aircraft engine turbo-supercharger - the only German turbo-supercharger that went into production at the end of WWII. BMW Flugmotoren GmbH was liquidated at the end of the war, rendering all staff unemployed. Dr. Müller had managed to sign a contract with the WMF (Württembergische Metallwaren Fabrik) for the development of a turbo-supercharger for wood gas vehicles. It is assumed that the already existing contacts between BMW and WMF for engine commodities were the foundation for this development.

A small group of former BMW employees began work on September 1st, 1945. The first two design drawings of Dr. Müller show a variable nozzle turbine turbocharger (September 1st, 1945), Fig. 4, and a free floating turbocharger (October 10th, 1945).

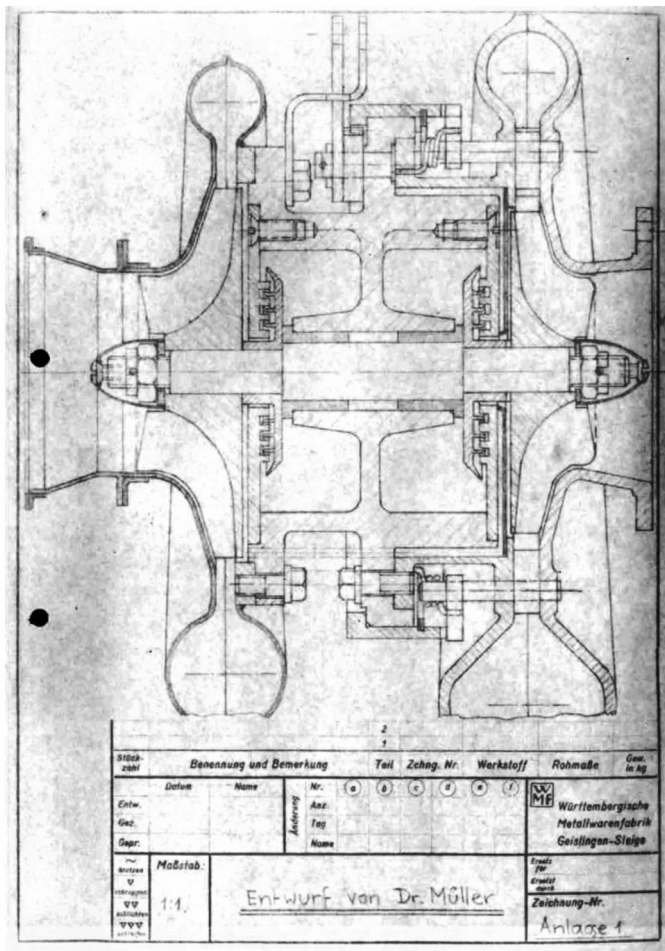


Fig. 4. WMF radial turbine turbocharger with movable vanes, drawing Sept. 1st 1945

The free floating turbocharger was the prime choice for the next development steps because of the lower complexity. The rotor had inner journal bearings with pressurized oil supply. The housings were made of gray cast iron or Silumin, an aluminum and silicon based light weight alloy. Both wheels had radial blades and were identical except for the difference in material.

The first test run occurred on March 21st, 1946 on a 4.7 dm³ Citroen engine powered truck, built in 1932. The engine operated, as planned, on wood gas, because gasoline fuel was rarely available in central Europe. The turbocharger had a compressor wheel of 115 mm and a turbine wheel of 112 mm diameter, and operated at 42.500 rpm. Problems arose from the journal bearings due to insufficient surface hardness, imbalance of the wheel assembly, overall excessive temperature levels and lack of oil supply. Ball bearings, however, weren't available during the time of war. Turbine wheels were milled out of Wolfram-containing tool steel (Fliegwerkstoff 1435).

Both of the compressor and turbine housings were manufactured from sheet metal in one of the following versions (July 24th, 1946), as this was one of the major businesses of WMF.

The bearings still caused many difficulties. An essential improvement to the bearing durability could be achieved by the introduction of the so-called heat throttle: the machining of a hollow shaft end on the turbine side to reduce the heat flow area.

At the end of 1946 the design was changed to use ball bearings which showed an increased reliability. This allowed future development efforts to focus on aerodynamic improvements. In January 1947, a turbocharger with ball bearings was installed in a wood gas truck for demonstration purposes, Fig. 5.



Fig. 5. Eberspächer turbocharger