

Development of High-Altitude Hybrid Fan Centrifugal Compressor System for Turbochargers and Utilization of AI to Improve Combustor Performance

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ABSTRACT

This opinion paper focus on the belief of the authors, that adding a fan or pre-compression stage in front of a centrifugal impeller typically found in commercial turbochargers has the potential to increase the overall pressure ratio of the turbocharger, which help with high-altitude operation. Additionally, this paper address conviction of the authors that the utilization of artificial intelligence and data science will improve combustor performance. The focus is on the development of high-altitude hybrid fan centrifugal and compressor system for turbochargers. Current attainable flight times of Unmanned Aerial Vehicles (UAVs) at high altitudes greatly hinder potential mission capabilities. Specifically, the US Army's small UAVs are propelled by automotive compression-ignition (CI) engines, which deliver the required high efficiency and low fuel consumption but lack the ability to ingest an adequate mass flow rate of low-density air into their compression cylinders at high altitudes. A hybrid fan- centrifugal compressor system will be developed and integrated onto these UAV engines to provide the air mass flow rate necessary to operate at 60% of maximum sea-level power while at 30,000 feet altitude; thus, reducing the hindrance of high altitude environmental factors on UAV missions. The combined system will be integrated on a dual shaft to allow for fan and compressor to rotate at different speeds. Dual shafts are, typically, used in turbojet engines for combined fan and axial flow compressors for delivering large air mass flow. This hybrid fan-centrifugal compressor system will offer higher pressure and mass flow rate to the current Army UAV engines than standard turbochargers, while maintaining simplicity and manufacturability.

Keywords: Artificial Intelligence, Data Science, Centrifugal Compressor, Compression Ignition, Fan Compressor, Fixed-Wing, High Altitude, Military, Supercharger, Turbocharger, UAV.

INTRODUCTION

The authors maintain that adding larger diameter fan section to the compressor wheel typically found in turbocharger has the potential to increase pressure ratio by the compressor and could improve operations at high altitude. For stater, it is worth mentioning that proposed hybrid fan

centrifugal compressor system focusses heavily on the compression side of the turbocharger. US Department of Defense (DOD) identified a critical need for small, reliable, high-efficiency engines for unmanned aerial vehicles (UAVs) at altitude 30,000-ft. The compression-ignition (CI) engines, also known as diesel engines, have been chosen by the Army as the preferred propulsion system for UAVs because of their high efficiency and low fuel consumption. Such engines require a turbocharger or supercharger boost system to deliver the required mass flow in the low air density at high altitudes.

The well-known automotive industry turbocharger and supercharger boost systems do not meet the required powers for performance at that altitude without modifications [1-10]. Turbochargers and superchargers consist of a centrifugal compressor system driven by a power source. A typical single-stage centrifugal compressor is shown in Fig. 1. The turbocharger's power supply to the compressor is usually generated from a radial turbine operated by the engine exhaust gases, while the supercharger's power supply is generated from the engine shaft or an electric source.

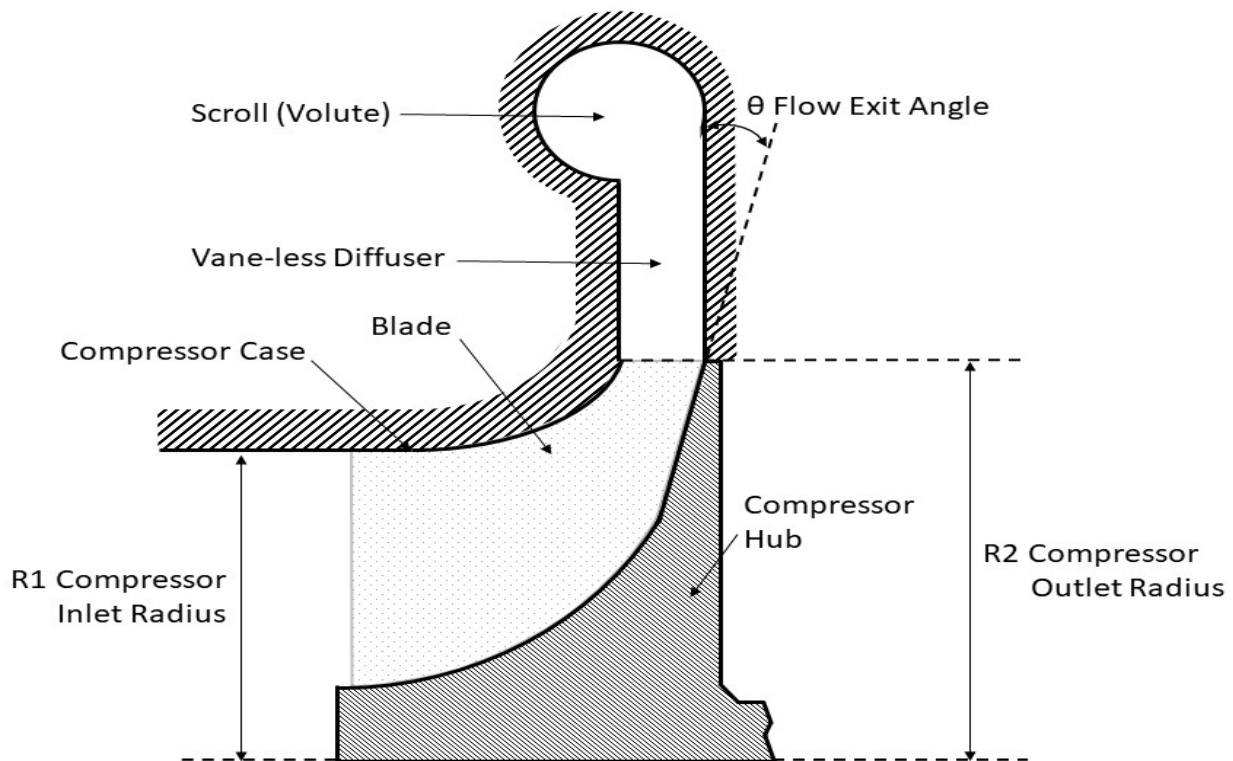


Fig. 1: Schematic for a Typical Centrifugal Compressor

From: Krain, H., and Hoffmann, W., "Centrifugal Impeller Geometry and its Influence On Secondary Flows," *AGARD Conference Proceedings*, Advisory Group for Aerospace Research and Development CP-469, 1989.

Application of centrifugal compressors for increasing air flow in diesel engines for UAVs flying at high altitudes, where the thermodynamic properties are lower, demand modification of existing automotive compressor aerodynamics, speeds, or materials. A multistage compressor design has an advantage of lower stage loading as compared to a single stage [11-20]. The use

of several stages with low pressure ratio linked together allows for multiplication of stages pressure to generate high pressure ratio. Since each stage has low pressure ratio they operate with higher efficiency and lower decibels [21-25]. A literature survey shows that multi-stage centrifugal compressors have been used to increase mass flow to diesel engines at high altitudes [15,19,20]. However, because of the nature of centrifugal compressors radial outlet flow, multi-stage compressors require complex ducting that leads to increased losses and compressor weight, Fig. 2. Back-to-back (Double Entry) compressor designs are the most used among the multi-stage compressors to increase air mass flow to CI engines, Fig. 3.

It is shown in reference [4] that a turbocharger pressure ratio of about 5 is required at 30,000-ft altitude for efficient operation of typical Voyager 550 engines. The use of a fan at the inlet of a single sided centrifugal compressor at that altitude will adequately increase compressor air flow to CI engines. Since fans must run at lower speeds than compressors due to their large diameter and the resulting high tip speed, a dual shaft or gearbox arrangement is necessary to deliver power to the compressor and fan from the same source. A schematic of the combined fan-compressor system is shown in Fig. 4. Dual shaft/gear box and bearing systems are typically used in turbofans and turboprop propulsion engines. These systems are available for purchase in the open market.

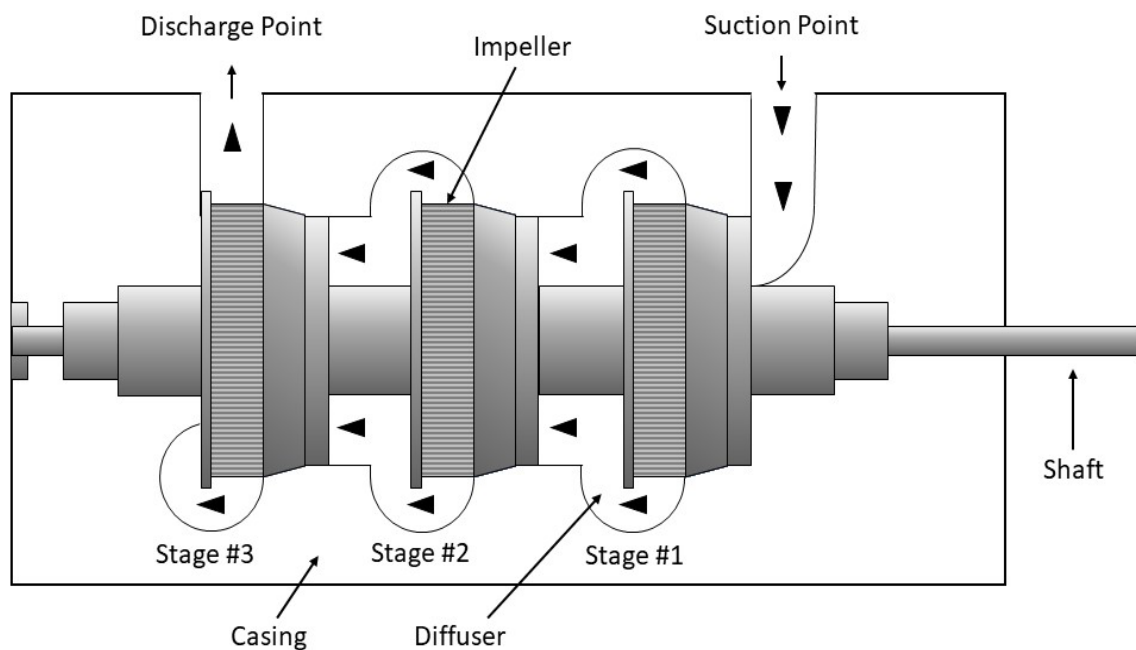
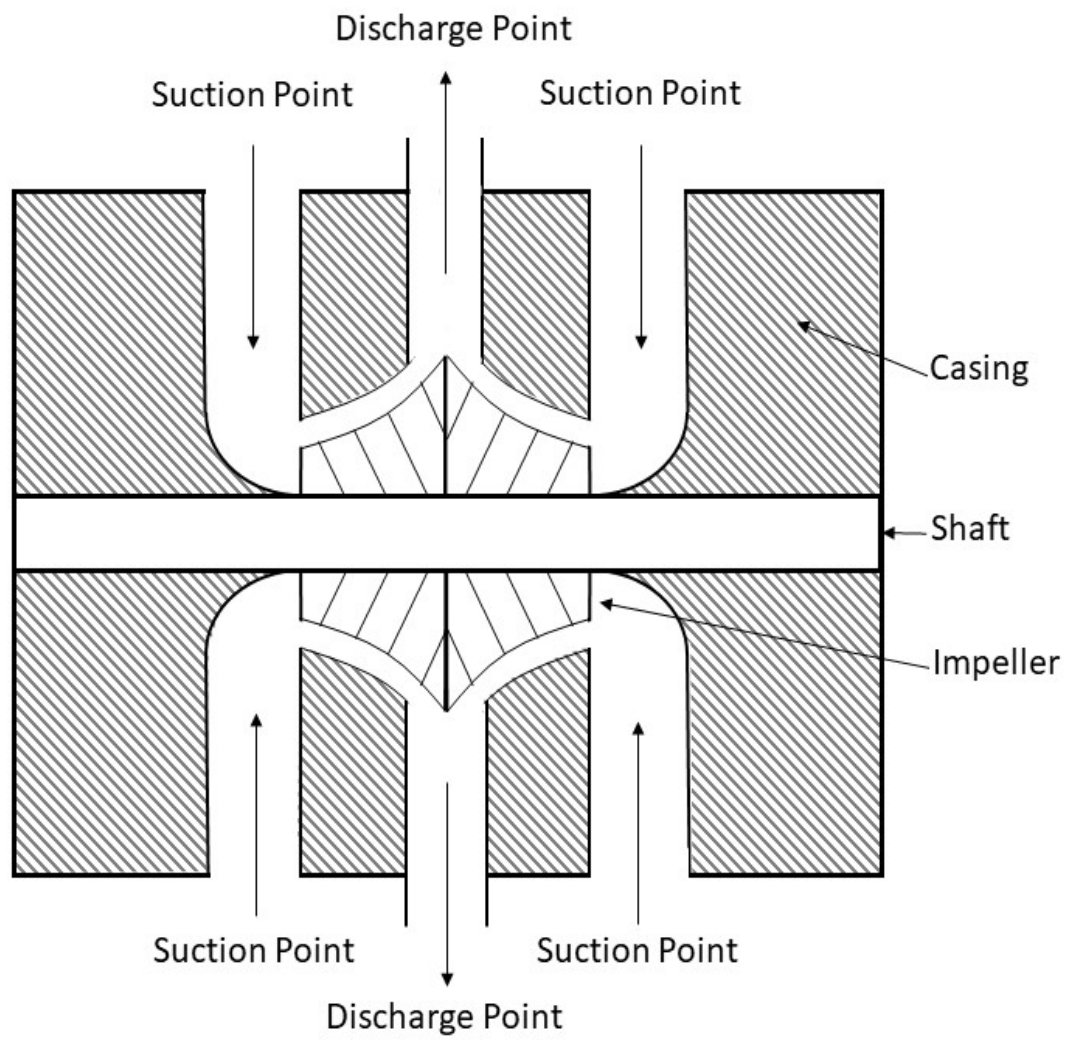


Fig. 2: Multi-Stage Centrifugal Compressor



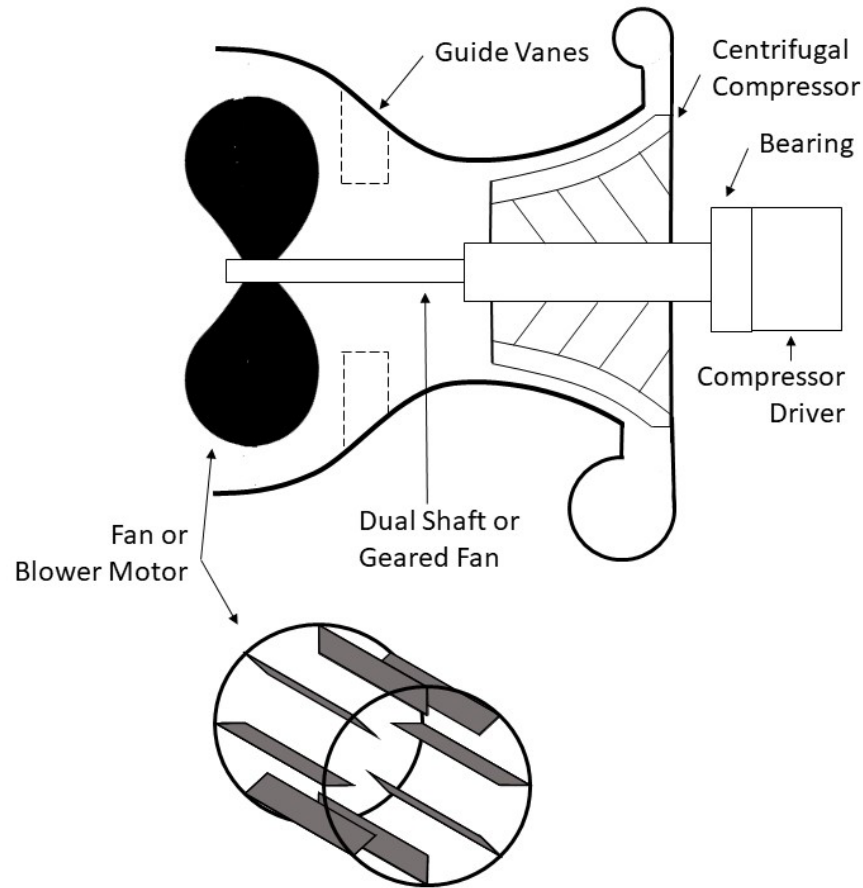


Fig. 4: Fan-Centrifugal Compressor System

TECHNICAL OBJECTIVES

An ideal design will be a fan-centrifugal compressor system for operation with a 180-hp Compression Ignition engine. The system will be designed:

- (1) For efficient operation between sea level and 30,000 feet.
- (2) For operation with required mass flow to achieve 60% power at maximum altitude.
- (3) To avoid compressor surge, shaft vibration, and blade deflection.
- (4) For a hardware life of 2,000 hours.
- (5) To weigh no more than 15 lbs.

While designing the system the following questions should be answered. Answering these questions is fundamental to the success of the fan-centrifugal compressor system and will provide the initial foundation for future development:

- (1) What type of fan will deliver the best performance for this system?
- (2) Can both the fan and centrifugal compressor be found off the shelf?
- (3) Does wind tunnel testing of the system at atmospheric conditions match the results of the simulation and analysis?

STATEMENT OF SCOPE

The hybrid fan-centrifugal compressor boost charging system should be designed to deliver the required mass flow for CI engines at altitudes ranging from sea level to 30,000-ft. A schematic is shown in Figure (4). Due to the difference in fan and centrifugal compressor functions, the fan must run at lower rotational speed as compared to the compressor. Therefore, dual shaft or gear box arrangements must be used to meet the optimum operations of these components. The large fan diameter (inlet area) will allow for ingesting large air mass flow compared to the air mass flow ingested by the centrifugal compressor alone.

The fan speed as well as its dimensions will be designed to meet the 60% of the sea level power required at 30,000-ft altitude. Typically, fans deliver high mass flow and low pressures. The centrifugal compressor in the current design will benefit from the modest increase of the fan pressure above the atmospheric pressure. That increase in the pressure obtained by the fan will help increase the compressor pressure ratio. The use of fan-axial compressor system is well developed in Aviation Turbofan engines. The dual shaft technology is also as well developed in counter-rotating propellers for efficient UAVs and Turbofan propulsion systems. Although the purpose of using the fan-axial compressor system and our design of fan-centrifugal compressor system is to deliver large mass flows, the function of the two systems is different. In the axial compressor system, the large mass flow is mostly delivered to a nozzle to generate thrust, while in the proposed centrifugal compressor system the large mass flow is completely delivered to the compressor of the turbocharger.

Different combinations of fan-centrifugal compressor geometrical and flow parameters will be explored:

- (1) Low and high aspect ratio fans. Two types of fans will be considered; the axial fan and the blower motor. Both fans are available off the shelf. They will be evaluated based on their performance when paired with a compressor, their weight contribution, and their compatibility with a dual shaft or gearbox system.
- (2) Transonic fan designs. Due to the large axial fan diameter, the blade tip speed will determine the efficiency of the fan performance. Different blade geometries such as forward and backward blade designs will be explored in order to reduce the tip speed to subsonic range for efficient fans.
- (3) Guide vanes between fan outlet and compressor inlet. A need may arise for using inlet guide vanes between the fan outlet and the compressor inlet stations to reduce the flow relative inlet velocity to the compressor, shown in Fig. 4. The use of inlet guide vanes for centrifugal compressors is a typical mechanism for controlling the compressor's mass flow and their relative inlet velocities.
- (4) Co- and Counter-rotating fan and centrifugal compressor systems. Co-rotating fan and axial compressor systems are well developed in aviation propulsion engines. In this study, we will test co-rotating fan and centrifugal compressor combinations with different speeds. We will test counter-rotating fan and centrifugal compressor combinations in the same way. A counter-rotating system is expected to eliminate the need for guide vanes between the fan outlet and the compressor inlet.
- (5) Vaned and Vane-less compressor diffusers. It is well known that vaned diffusers result in a more efficient compression process. However, vane-less diffusers are the most suitable for the current design because of the weight penalty of the vanes for a flying engine. The efficiency versus weight of vanes will be evaluated.

- (6) The one and a half stage centrifugal compressor design of reference [12]. These one and a half centrifugal compressor patents by one of the authors of this proposal will be considered because of its advantages in achieving high pressure compression ratio efficiently. This high-pressure compression ratio is achieved with the use of complex ducting arrangements. The added efficiency versus added weight of the system will be evaluated.

Building and testing of the fan-centrifugal compressor system will commence once the design and analysis is complete. If both fan and centrifugal compressor are chosen off the shelf, then assembly with an electric drive motor and dual shaft or gearbox is required. If one or both fan-centrifugal compressor components has been designed from scratch, then there will be a fabrication process before assembly with the electric drive motor and dual shaft or gearbox. The testing will consist of component table testing and wind tunnel testing at sea level conditions. Test results will be compared with simulations and performance analysis results before performing simulations and analysis on the system to prepare for testing at altitude. The authors' assertions should be supported after a fan-centrifugal compressor system has been designed and tested with an electric drive motor, and simulations and performance analysis has confirmed design parameters at 30,000 feet.

UTILIZATION OF AI TO IMPROVE COMBUSTOR PERFORMANCE

The fan-centrifugal compressor system as discussed thus far, is the cold side of a turbofan engine. Fans are primarily designed to provide thrust rather than compression. A turbocharger would typically be driven by excess energy in the exhaust from the engine. It is this hot turbine section that most problems that hinders performance are experienced at high altitude. This is where integrating AI to mitigating the problem to improve combustor performance becomes advantageous. Following successful building and testing of the system using an electric drive motor, the fan-centrifugal compressor system will be matched with an internal combustion engine for combustion testing. The testing will be able to demonstrate the full capability and compatibility of the system with a CI engine.

AI could be used to control the starting, throttling, and shut off modes of a combustor, automate and optimize the engine performance at different operating conditions and preventing/mitigate engine failures. Other beneficial AI integration could include investigating the working process inside the combustion chamber for fuel and parameters of the inlet air flow. A machine learning training model of gasification and combustion of fuel in combustor could be developed and validated by comparison numerical results with available from literature of experimental data. The machine learning model could be used to predict combustor performance parameters. This will show if there is a significant variation for subsonic flows equivalence ratio and combustion efficiency within wide range of air mass fluxes. Additionally, pressure oscillation in the combustor called thermoacoustics has been studied over the last decades with mixed success. Traditional engineering methods fall short of predictability during the development of engines due to a high sensitivity of thermoacoustics with respects to barely known input parameters. Machine Learning could be utilized to predict and understand thermoacoustic in the engine. Cyber-physical systems could be installed which could be used to analyze and monitor systems and take automated decision.

ANTICIPATED BENEFITS / POTENTIAL COMMERCIAL APPLICATIONS OF THE RESEARCH

The centrifugal air compressors market would experience the highest compound annual growth rate of 18.3% during the period 2015-2021. This rapid growth can be attributed to its capability to generate a high amount of air pressure from the angular momentum of its rotating impellers. The proposed compressors will have applications in many fields: (1) Defense (Army UAVs, Navy hydrodynamic engines), (2) Power generation (booster compressors for co-generation plants and compressors for hydroelectric power), (3) Oil and gas re-injection and extraction, (4) Aviation (helicopter engines, small jet engines, and turboprop engines), (5) Food processing, (6) Liquid rocket engines (cryogenic and fuel gas boosting), (7) High-pressure CO₂, and supercritical power cycles, (8) Fertilizers (ammonia, urea, nitric acid, melamine), and (9) Medical (blood flow applications).

DISCUSSION

The authors presented information to support their assertions that high-altitude hybrid fan centrifugal compressor system for turbochargers has the potential to deliver higher pressures and mass flows when compared to conventional systems. Information was also presented to support the notion that utilization of AI to improve combustor performance. A hybrid fan-compressor could be useful for both military and commercial aircraft. Taken at face value, it seems that the authors succeeded in what they set out to do. However, the proposed system lack details of how a successful compression technology would be integrated with the rest of the turbocharger. Also lacking is analysis of structural dynamics with density lapse.

The use of a fan as a pre-compression stage may add complexity and weight to the system (two shafts, additional bearings, etc.). The use of off the shelf components as discussed as one of the alternative options, might seem appealing, it may limit a would-be developer the ability to asses if the components will or will not have any resonances or surge issues, and identification of technical risks. The recommended further research, is the study of how the boost system will be powered or driven in the unconventional architecture (inconsistent with common practice in fluid machinery) of the addition of a fan to increase pressure rise for the turbocharger.

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