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In-Flight Nozzle Morphing Mechanism for a high speed Aircraft using a Retractable Nozzle Section

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ABSTRACT

Aircraft Engine Nozzles are designed to operate at a predetermined flight condition. Any variation of the aerodynamic environment, leads to reduction in the nozzle efficiency, which is the efficiency with which the potential energy is converted to the kinetic energy in a nozzle. To improve the aerodynamic performance of a convergent jet nozzle, it can be morphed into a convergent-divergent nozzle and vice versa, depending on the flight regimes, whether subsonic or supersonic respectively. Nozzle morphing can become a subject of extreme importance considering the aspect of nozzle efficiency. This paper presents a method for morphing the engine nozzle of an aircraft flying at supersonic speed. To demonstrate the nozzle efficiency, a CFD analysis is done on a convergent and convergent-divergentnozzle by simulating the flow using the software of GAMBIT for meshing and ANSYS FLUENT, for post-processing. An important aspect of extension and retraction of Retractable Divergent Nozzle Section, through hydraulic actuator system, is being proposed. This mechanism can be practically implemented. Though there are many structural and mechanical studies required for this mechanism, this paper mainly deals with the aerodynamic considerations of the generated idea.

Keywords: Choke condition, Convergent nozzle, Convergent-Divergent nozzle, Critical nozzle pressure, Retractable Divergent Nozzle Section

1. INTRODUCTION

A propelling nozzle can accelerate the combusted gas to subsonic, sonic, or supersonic velocities depending upon the application of the engine. Their internal shape is again governed by the flight regime in which the engine incorporating it is designed to operate. Moreover, the propelling nozzle may have a fixed geometry, or it may have a variable geometry to give different exit areas to control the operation of the engine when equipped with an afterburner [1] or a reheat system. However, there are three fundamental, yet crucial designs of a nozzle- convergent, divergent and convergent-divergent. Each of the three designs is limited to particular flight regime. A convergent nozzle finds its application in most of the commercial jet engines operation in subsonic or transonic speeds or even up to lower supersonic speeds. However its operation is limited to critical nozzle pressure ratio [2] value (about 1.8:1) beyond which the convergent nozzle will choke- a condition in which the mass flow rate will not increase with further decrease in the downstream pressure environment while upstream pressure remains fixed. A divergent nozzle is usually used in rocket engines and scramjet engines where the exit velocity is in the hypersonic range. Convergent-divergent nozzle on the other hand is a combination of both; convergent as well as divergent. Engines capable of supersonic flight have convergent-divergent exhaust duct features to generate supersonic flow.

2. LITERATURE SURVEY

The task of the exhaust nozzle is to convert gas potential energy into kinetic energy which is necessary for generating thrust. This conversion is achieved solely by the geometrical shape of the nozzle, which is basically a tube of varying cross-section. However, not every nozzle type performs in similar manner. Depending on the type of aircraft and the design flight speed, different type of nozzles are used. In particular, distinction is made between convergent and convergent-divergent nozzles. There has been a huge gap between subsonic flight and supersonic flight due to various factors. For example, the engine employed with convergent nozzle is limited to higher subsonic speeds (or even low supersonic speed). This is mainly because beyond the particular value of nozzle pressure known as critical nozzle pressure, the flow in the nozzle starts to choke resulting in incomplete or under-expanded jet, thereby reducing the amount of thrust produced by the nozzle. As a result pressure will rapidly tend to equalize causing the jet to expand in an undesirable radial direction, with particle inertia now causing the pressure in the middle of the jet to fall below the ambient. Under-pressure will then trigger contraction of the jet such that a zone of over-expansion is succeeded by a zone of under-expansion.

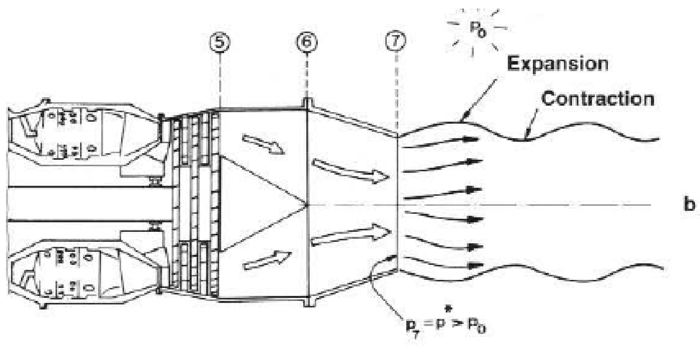


Figure 1: An engine with convergent nozzle under supercritical operation

In case of convergent-divergent nozzle, a fixed type is badly suited for aircraft application because the exhaust area cannot be matched to the varying conditions of ambient pressure and engine power settings. Furthermore, such nozzles would be long and heavy. For this reason, engines using thrust augmentation [4] feature a variable-geometry nozzles which are often complicated in design and again its limitation is governed by the convergent-divergent nozzle which operates above specific nozzle pressure ratio, otherwise a backflow would result due to positive pressure gradients being set up along downstream of the flow. Thus we can see that both the designs are limited by their speed of operation. Despite various augmentation methods are developed to increase the thrust produced by the engine beyond its normal value, the geometric constraints of the nozzles limits the use of the engine to specific flight speeds suitable for nozzle operation. The work presented here builds on the efforts of the researchers around the world to unite high performance designs for each flight regime into single airframe. In this paper we propose an idea to change the shape of the nozzle as per flight condition, i.e. a convergent nozzle can be morphed into a convergent-divergent nozzle and vice versa by using hydraulic mechanism. The main advantage of this concept would be-from aerodynamic point of view-that a single engine can be effectively used in subsonic as well as supersonic flight speeds since the nozzle can be morphed as required, thereby providing flexibility.

3. COMPARISON OF C AND C-D NOZZLE

A nozzle is crucial part of the jet engine as the combusted gas after imparting mechanical energy to the turbine is converted into high velocity gas that generates the required thrust to propel an aircraft. It also helps being a downstream restrictor to determine the operation of the compressor and fan. Propelling nozzles may have fixed or variable geometry to provide difference in exit areas to for controlling engine operation when there exists an afterburner or reheat system. Afterburning system in a C-D nozzle tends to requirement of a variable throat area. At supersonic flight regime, generation of high pressure ratios occur which leads to usage of variable area divergent sections.

3.1 Operation Principles:

Nozzle constricts the airflow at its throat to increase the pressure within the engine so that the flow chokes and then the exhaust gases start getting expanded to or approximately equals to atmospheric pressure and thus form a high speed jet to generate required propulsion for the vehicle. Constriction to the flow and back-pressure are two general roles of a nozzle. The temperature and pressure of the gas generate energy to accelerate the stream. Adiabatic expansion of gases takes place with low loses and high efficiency. The ambient pressure of exhausts, efficiency of expansion and entry level pressure and temperature of the nozzle play an important role in deciding the exit velocity of the gases.
Jet of exhaust gases having speed greater than aircraft are released by the air-breathing engine which produce a net forward thrust in the airframe.
Nozzle variety based on shape:

Convergent Nozzle

A convergent nozzle chokes [3] when the pressure ratio is above the critical value (generally 1.8:1) and results in expansion to atmospheric pressure taking place downstream of the throat in the jet wake. Gross thrust is created by the jet momentum, but the imbalance in throat static pressure and the atmospheric pressure generate some pressure thrust.

Divergent Nozzle

Supersonic air speed intake into a divergent nozzle results in its usage in supersonic application-based airborne vehicles, like Scramjet.

Convergent-Divergent (C-D) Nozzle

C-D nozzles are used to generate supersonic exhaust flow in airborne vehicles. The hot exhaust gases pass through three flow phases. First, the hot exhaust gases leave the combustion chamber and converge down to the throat of the nozzle. This cause the flow to become subsonic and attain choke region which is at sonic zone, i.e. Mach one. Then the mass flow rate is set through the system and divergence point initiates where flow expands to supersonic Mach number isentropically. This depends on the area ratio of the nozzle exit to the throat. Static temperature and pressure decreases downstream due to supersonic flow expansion and thus it determines the exit temperature and pressure. Speed of sound at exit is determined by exit temperature and thus it determines the exit velocity. Thrust production of the nozzle is determined by the exit pressure, velocity and mass flow through it.

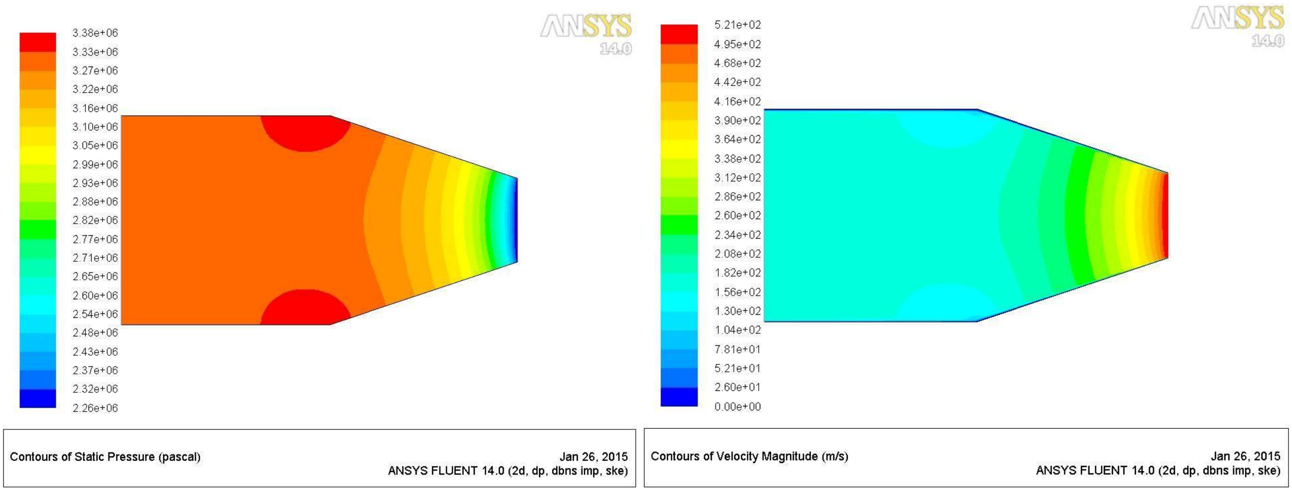
3.2 Nozzle Throat- Area Equation:

$$(1 - M^2)\frac{dV}{V} = \frac{dA}{A}$$

where *V*= velocity, *A*= area and *M*= Mach number.

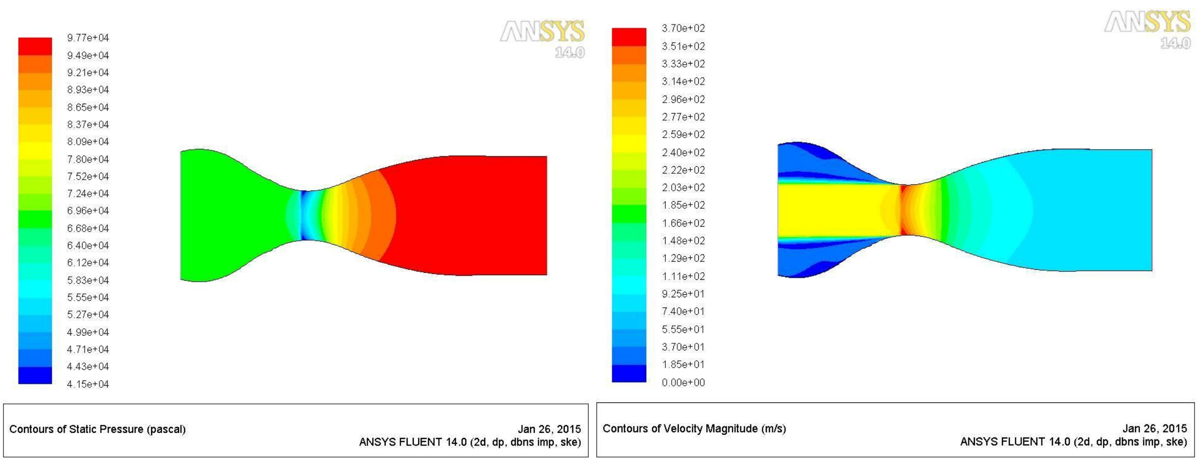
For subsonic flow (*M<1*), increase in area (*dA>0*) causes flow velocity to decrease (*dV<0*). For supersonic flow (*M>1*), increase in area (*dA>0*) causes flow velocity to increase (*dV>0*).

4. CFD ANALYSES



(a)Static Pressure **(b)Velocity Magnitude**

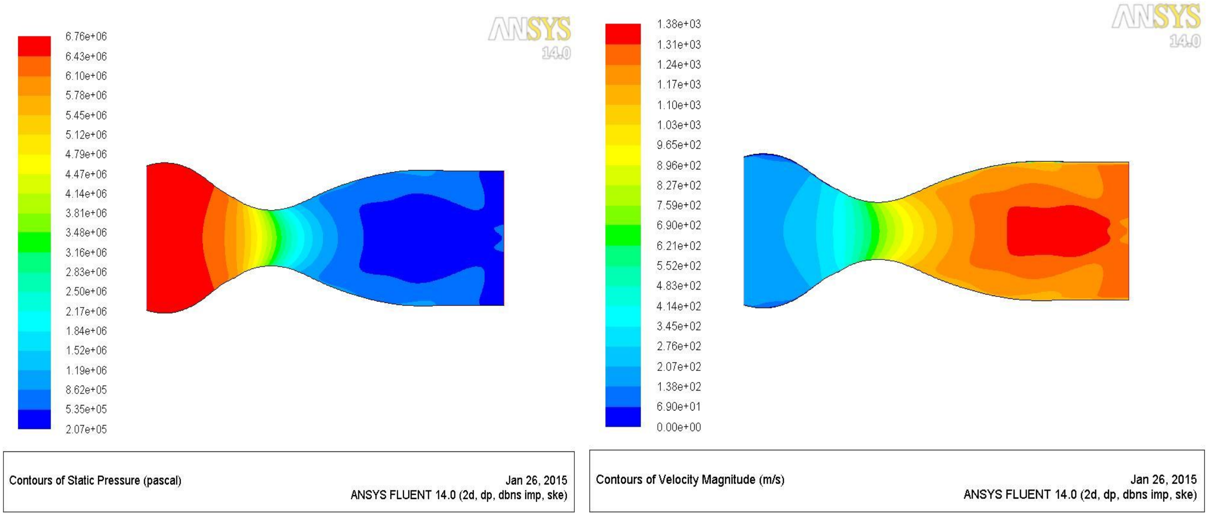
Figure 2: FLUENT analysis of convergent nozzle at subsonic conditions



(a)Static Pressure **(b)Velocity Magnitude**

Figure 3: FLUENT analysis of convergent-divergent nozzle at subsonic conditions

From FLUENT analyses of two nozzle designs, we can observe from figure (1) that a convergent nozzle performs satisfactorily in subsonic flight regime, whereas a convergent-divergent nozzle-which can be observed from figure (2)-experiences choke at the throat resulting into reversed flow as the pressure builds up in the divergent section. Hence it can be affirmed that a convergent-divergent nozzle is not suitable for subsonic flight conditions especially at low subsonic speeds.



(a)Static Pressure **(b)Velocity Magnitude**

Figure 4: FLUENT analysis of convergent-divergent nozzle at supersonic conditions

From figure (3) we can clearly observe that at supersonic flight regimes, the convergent-divergent nozzle will perform as required with favorable pressure gradient being set up downstream of the flow. Thus we can observe that the two nozzle designs are restricted to their respective flight regimes.

5. Mechanism of Extension and Retraction of Retractable Divergent Nozzle Section (RDNS)

The C-D Nozzle generally can be divided theoretically into two parts: Convergent section and Divergent section. Convergent section is fixed at its position inside the inner cowling of the engine. The requirement is to enable the movement of the RDNS so that divergent section of the nozzle can be deployed at the required position just next to the convergent section so that a complete shape of De Laval nozzle can be acquired with maximum efficiency. So starting with divergent section, there are hinges attached just at a few length after the initial portion of divergent section. And hydraulic actuators are attached just before the hinged section of divergent nozzle section. When conversion from convergent section to C-D section takes place, the divergent section is retracted out by means of actuators placed ahead of the whole nozzle. On extending the retractable part completely, the hydraulic actuator system starts operating and the divergent section of the nozzle is pressed down to get connected and locked with the convergent section so that an exact C-D nozzle is formed. The hydraulic actuators are given as feedback to the system operation by getting pressure from the pressure gauges so that the retracted divergent section is not blown off due to exiting mass of the exhaust gases. The convergent section ending and divergent section initial part have a cut-out section which goes into the divergent section once it's placed in position to form the shape of C-D section. The hinges come into play to avoid collision of RDNS with the convergent section while retraction or extension takes place. The hinges have mechanically shaped protruding metals on both inner and outer side at a certain angle to avoid further movement once a required shape is acquired. The whole mechanism is built to increase the efficiency of the system as the thrust can be provided according to requirement at certain Mach number of the flight.

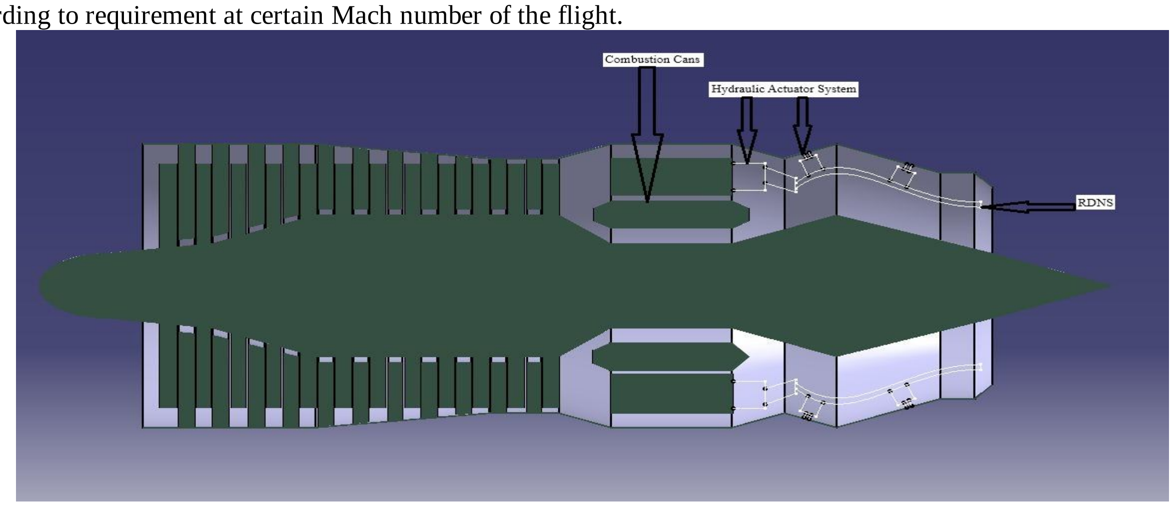


Figure 5: Two dimensional view of engine equipped with RDNS

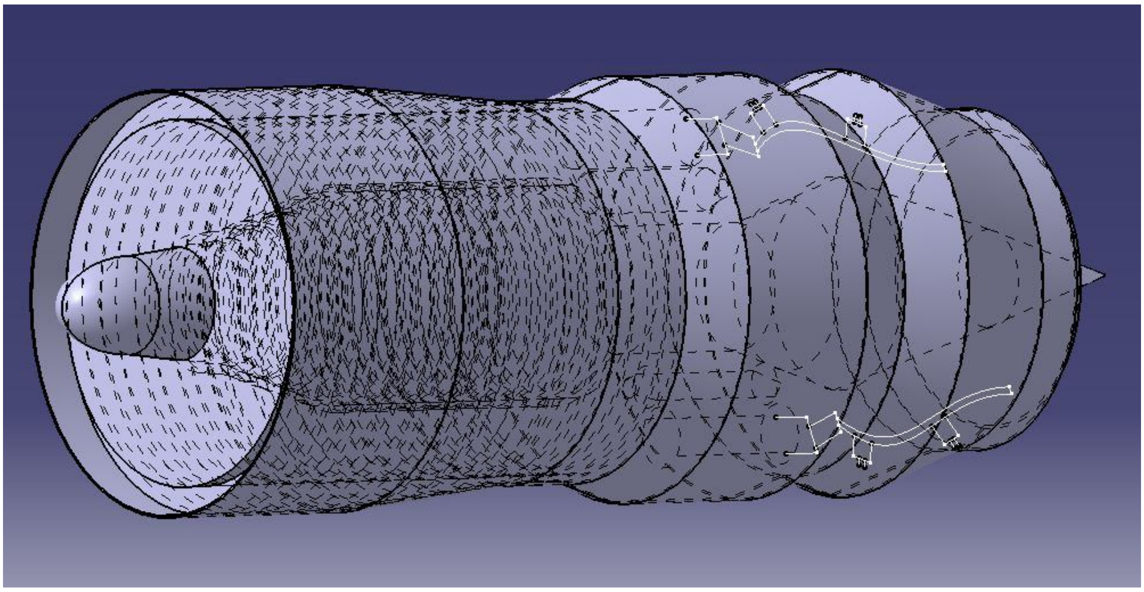


Figure 6: Three dimensional view of the engine with RDNS installed

6. CONCLUSION

In this paper we proposed a new mechanism to transform a convergent nozzle into convergent-divergent nozzle by using hydraulic actuators that perform the extension and retraction of the divergent nozzle section. From CFD analysis we were able to determine the limitations of the nozzle designs beyond their respective speed of operation and we were further able to design appropriate mechanism with intention to combine the advantages of these nozzles into a single unit to increase the range of flight regime. The nozzle transformation makes an engine highly flexible to use, resulting into development of airplane that can perform myriad of operations under wide flight regimes. Next generation combat aircraft can adopt such mechanism in order to carry out surveillance as well as combat operations as per the situation demands. The detailed CFD analyses including the flow analyses during transition phase (i.e. when the divergent nozzle is extended and vice versa), detailed mechanical structure of the nozzle and the hydraulic actuators will be investigated in our further study.

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Navuday Sharma, Pritam Kumar Pratihari and Jayraj Inamdar are currently in final year of B-Tech Aerospace + M-Tech Avionics (Dual Degree) at Amity Institute of Space Science and Technology, Amity University, Noida, India. They generated a new idea for nozzle morphing. This project which will be proceeded further considering the structural and mechanical aspects of the design, which may lead to practical implementation of the design.