Effect of leading edge sweep on the performance of cavitating inducer of LOX booster turbopump used in semicryogenic engine

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Abstract. As a part of the developmental effort towards the realization of a staged combustion cycle based liquid rocket engine, a program on simulation of the LOX booster pump for performance characterization has been taken up. Earlier reported work shows that the pump inducer works satisfactorily under cavitating conditions for the throttling range varying from 90% to 113%. However stall occurs below 90% of the designed flow rate which is to be strongly associated with the inlet backflow vortices due to flow separation [1]. It is envisaged that leading edge sweep may help in to controls the incipience and growth of the backflow vortices at the inlet leading edge tip of axial flow inducer leading to a wider operating range. In this paper, steady state 3D CFD analysis of rotating inducer is performed to examine the effect of leading edge sweep on the performance of axial flow LOX pump inducer using ANSYS® CFX and has been compared with the performance of the inducer reported by Mishra and Ghosh [1].

1. Introduction
The primary constraint on space enterprises is the high cost of escaping Earth’s gravity. Therefore, for manned space mission and deep space probes, reusable launch vehicles are contemplated to be used. One of the technological options towards this endeavour is a semicryogenic engine based on high pressure, oxygen rich, staged combustion cycle with LOX and hydrocarbon fuel [2].

For high thrust, a mission with high specific impulse, a turbopump propellant feed system offers overall weight reduction, high power to weight ratio with increased payload capacity. This turbopump feed system has at least on booster pump to ensure cavitation free operation at the main pump inlet. Cavitation is the vaporization of the liquid in regions of low pressure, and it has negative consequences lead to substantial losses finally contributing to the degradation of pump performance and higher cost of the mission. This makes cavitation an important issue in design and operation of the booster turbopump.

The LOX booster turbopump is typically designed to operate in slightly cavitating condition and permits the main pump to work at higher speeds [3, 4]. The term cavitating refers to the fact that the pump is capable of operating over a broad range of incipient cavitation before a noticeable pump head drop off.

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The axial flow inducer is the anti-cavitation component to the upstream portion of the turbopump. The principal objective of an inducer is to preclude cavitation intended in the following stage and to improve the cavitation performance of booster pumps by increasing the inlet pressure to a level adequate to allow main LOX pump to operate without excessive loss of performance due to cavitation.

It has been visualized that they have complex, highly three-dimensional internal flows, especially at off-design conditions [5]. The optimum design, therefore, is to obtain the required suction specific speed and head rise of the inducer without introducing undesirable cavitation under all operating conditions [6]. Backflow vortices tend to form on the leading edge causing cavitation damage to the blades tip and a variety of vibrations associated with flow instabilities such as tip vortex cavitation, backflow vortices and stall occurs at an off-design condition that may be detrimental to the inducer operability. Avoidance of these cavitation instabilities is an essential issue for the design of reliable inducers.

In the previous study [1], it was observed that at the design flow rate, the tip vortex starts from the blade leading edge at the tip. This suggests that the interaction of the tip cavity with the leading edge of the adjacent blade would be avoided by moving the leading edge of the blade tip downstream by giving a larger sweep as compared to the original axial inducer without sweep.

In this paper, a design modification has been introduced to the axial flow inducer leading edge to impart large backward sweep because of their structural robustness and favorable effects on cavitation. This modified leading edge backward sweep as reported in the literature [7] helps to minimize the production of cavitation and deleterious consequences of cavitation on the steady state performance of a pump and to improve cavitation and stall margin with wider operating range.

2. Objectives

The design methodologies for turbopump found in the literature [6] [8-12] still today, completely do not explain the influence leading edge sweep of the inducers on their performances. This paper is an attempt to predict then effects of leading edge sweep on the performance of the cavitating inducer. The objectives of the work presented herein are as follows:

1. To compare the performance of the backward leading edge sweep inducer with the original axial inducer reported in [1] for 100% thrust condition.
2. To investigate backward leading edge sweep effect on the performance as well as on the onset of cavitation stall phenomenon at different on design and off-design flow rates and inlet total pressure.
3. To explore whether instabilities such as recirculation, tip vortices, and cavitation-induced unsteadiness exist for an inducer with backward leading edge sweep.

3. Methodology

3.1. Geometry of axial flow inducer

The CAD models of the axial inducers designed for a booster turbopump of staged combustion cycle based rocket engine have been generated using Autodesk Inventor software. The major dimensions are shown in figure 1 (a) and figure 1(b).

The axial flow inducer geometry reported in [1] was modified by imparting a backward leading edge sweep angle of 50° with a radius of 55mm, as shown in Figure 1(b).

3.2. Simulation methodology

A grid independence study has been performed considering static pressure at the outlet of the inducer as independent variable. The independence of the numerical results from the number of grid points has been confirmed by simulating the computational flow field with different density of meshes according to the previously reported work [1]. It has been observed that there is little variation in the above parameter above 1.8 million nodes as shown in figure 2.
The unstructured, patch conforming mostly tetrahedral meshing elements were generated using automatic meshing in ANSYS meshing software. The discretized computational domain consists of about 1.8 million nodes and 9.89 million elements.

To ensure sufficient grid refinement at the boundaries, the value of $y^+$, the dimensionless distance of the first grid point from the blade surface, is kept around $30 < y^+ < 60$ at all the boundaries. To ensure $y^+$ value is closer to 1 near the leading tip for capturing low pressure regions prone to cavitation, high grid density cells with small aspect ratio has been considered in that region. Different mesh statistics are given below in Table 1.

Figure 1 (a) Inducer without sweep

Figure 1 (b) Inducer with backward leading edge sweep

Figure 2 Grid sensitivity analysis result for axial inducer with sweep
The steady-state calculations of the 3D flow of the rotating axial flow inducer have been performed using ANSYS® CFX, to investigate the effects of leading edge sweep on performance. RANS (Reynolds–Averaged Navier–Stokes) equation based SST-\( k\)-\( \omega \) (Shear Stress Transport) turbulence model with automatic wall treatment has been used for turbulence closure [13]. This model indicated useful understanding for the experimental results where similar kinds of turbomachines were simulated [14, 15]. This programmed wall treatment function will automatically switch between the low-Re boundary layer formulations for fine meshes to the wall function treatment for coarse meshes. The SST model is a combination of the best elements of the \( k\)-\( \varepsilon \) and \( k\)-\( \omega \) model and therefore accurately predicts the boundary layer flow and separation [16]. A high-resolution advection scheme with first-order turbulence discretization has been used [14].

### 3.3. Boundary conditions

The boundary conditions of the present work are similar to that of former work [1]. At the inlet of the axial flow inducer, subsonic total pressure has been defined in stationary frame with normal flow direction and inlet total temperature. The mass flow rate is set at the exit. In the present simulation, the turbulent intensity was assumed to be 10\%, and all the walls were considered to be smooth, adiabatic and having no slip.

The simulations were carried out until the residuals decreased to \( 10^{-4} \) (Root Mean Square) for all the conservation equations. The convergence of the solutions was ensured by monitoring the residual values and variables of interest.

Different input parameters required to simulate 100\% nominal thrust condition are given below in Table 2.

| Parameter | Input data |
|-----------|------------|
| Stationary frame total temperature at the inducer inlet, \( T_{0,i} \) [K] | 91 |
| Stationary frame total absolute pressure at the inducer inlet, \( p_{0,i} \) [M Pa] | 0.47 |
| Mass flow rate [kg/s] | 442 |
| Design speed, \( N_d \) [rpm] | 7016 |

For reusable launch vehicle engine, thrust may be throttled during the mission. Therefore, the parametric analysis of LOX pump axial inducer has been performed to predict the off-design performance over a broad range of flow coefficients and head coefficient values at designed rotational speed (\( N_d \)). Here \( Q/Q_d \) is varied from 0.60 to 1.13 and inlet total pressure of the axial flow cavitating inducer ranges between 0.1 to 0.62 MPa respectively. Then, the performance and design parameters obtained through steady state CFD analysis of axial inducer without sweep in earlier reported work [1] are compared with inducer with backward leading edge sweep.

### 4. Results and discussion

A detailed comparison for 100\% nominal thrust condition has been performed between the previous numerical predictions of the performance for an inducer without sweep [1] and the results taken on backward leading edge inducer. The values of various performance parameters are summarized in Table 3.
The values of head rise coefficient and the total head developed for backward leading edge sweep inducer are more as compared to the inducer without sweep [1]. The hydraulic efficiency and thoma cavitation factor of the inducer with the sweep are less as compared to axial inducer without sweep. This ensures that modification of the leading edge geometry with large backward sweep significantly degrade the suction performance of the axial inducer and more prone to cavitation at design flow coefficient.

4.1. Comparison between different performance characteristic curves for off-design conditions

The design flow coefficient for swept back inducer is $\phi = 0.09$ is same as the axial inducer reported in [1]. While it has been observed but we observed from the figure 3 that the inducer with backward leading edge sweep performs reasonably well down to about 60% of the design flow coefficient. Most of the range of flow coefficient higher than designed flow coefficient and the hydraulic head developed is higher than that of without sweep inducer, except at designed point.

The depression in the head curve ($\psi - \phi$) is indicative of flow separation, and this region of the curve can, therefore, be quite sensitive and often leads to fluctuating pressures and flow rates through the excitation of the stall mechanisms. Stall refers to a recirculating fluid zone. Stall indicates the region with a positive slope in the $\psi - \phi$ curve. The decrease in the head rise is associated with a fast growing stall region when the flow rate is decreased. The slope of $\psi - \phi$ curve in case of large sweep inducer is less steep than that of the inducer with sweep. It may be observed that the stall margin and hence, the stable operating range of the pump has widened in case of the inducer with sweep. [17, 18, 19]. This change in stall point location is as a result of larger leading edge sweep than the earlier one.

| Performance parameter                  | Inducer without sweep [1] | Inducer with large leading edge sweep |
|----------------------------------------|---------------------------|--------------------------------------|
| Specific speed, $N_s$                  | 103.60                    | 92.85                                |
| Total head rise coefficient, $\psi_p$  | 0.35                      | 0.41                                 |
| Static head rise coefficient, $\psi_s$ | 0.28                      | 0.31                                 |
| Total head developed, $H$ [m]          | 147.92                    | 169.74                               |
| NPSHa [m]                              | 32.26                     | 32.14                                |
| Thoma cavitation factor, $\sigma$      | 0.220                     | 0.189                                |
| Torque power, $P_t$ [kW]               | 707.48                    | 860.85                               |
| Power due to head difference, $P_h$ [kW]| 637.48                    | 736.02                               |
| Hydraulic efficiency, $\eta_h$         | 90.10%                    | 85.49%                               |

Table 3. Performance parameters for cavitating inducer at 100% nominal thrust condition

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![Figure 3. Overall performance characteristic, $\psi_p - \phi$ curve at $N_d$ Constant](image1.png)

![Figure 4. Hydraulic efficiency, $\eta_h$ Vs. Flow Coefficient, $\phi$ at constant designed speed $N_d$ Constant](image2.png)
Figure 4 depicts that the maximum efficiency, 86.87% occurs near to designed flow coefficient for the inducer with leading edge sweep. This is slightly lower than that of reported in [1]. Hydraulic losses and cavitating instabilities increase at off-design conditions result in steep fall in efficiency curve below the stalling point [7]. It has been observed from figure 5, that the effect of stall is less pronounced for low pressure ratio [20, 21]. Hence, the inducer with sweep operates stably well down to about 60% of the design flow coefficient and could avoid circulatory flow due to vortex that may lead to cavitate surfaces.

4.2. Effect of leading edge sweep on cavitating flow field for various operational parameters

Detailed analysis has been performed to investigate the effect of leading edge sweep on the flow field for various operational parameters.

4.2.1. Effect of mass flow variation.

Numerical computations have been performed for the inducers at a constant speed for different design flow rates. Figure 6 (a) and figure 6 (b) depict that the size of the backflow region grows as flow coefficient is decreased below designed flow coefficient value i.e. 0.09.

This ``backflow-induced swirl'' eventually separates the flow from the blade surface thus creating a stall condition at leading tip of the inducer with leading edge sweep [22]. This flow in the inducers along with backflows both upstream and downstream at the off-design conditions lead to a drop in efficiency [20].

The accelerated backflow has a high swirl velocity at the leading edge subsequently that leads to strong rediffusion of vortices to the core flow and reduce the vortex core region at low flow rate through the circulatory flow as shown in figure 7. This leads to rising of the secondary flow with the core flow through reducing the efficiency.

4.2.2. Effect of inlet total pressure variation.

The cavitation inception is usually not a severe problem, but as the inlet total pressure is further reduced, increasing the regions corresponding to static pressure less than or equal to (isovolumne) vapor pressure i.e. the zone of cavitation grows extensively but the pump head remains constant [9, 23]. Figure 8. depicts the isovolume distributions for the cavitating inducer with backward leading edge sweep corresponding to the pressure equals to or less than vapour pressure i.e. 0.11022 MPa. It has been observed from the inducer without sweep that the isovolumes were created at the tip of blades that may lead to a tip vortex cavitation.
In the present inducer the isovolume are attached to the blade surface and hence there may be the possibility of “fixed” or “attached” cavitation. In the earlier inducer, the regions with pressure below vapor pressure were growing through the entire inducer whereas in this case the isovolumes are moving along the blade surface. Here the inducer with sweep may have greater operating range. However, the “fixed” cavitation, if it occurs, may lead to erosion of blade surface.

5. Conclusion

In this paper performance of the inducer with leading edge sweep designed for the LOX booster turbopump of a staged combustion cycle based rocket engine has been studied and the has been compared with that of an inducer without sweep.

1. It has been observed from the performance characteristics curves that the operating range of the inducer [1] designed for the LOX booster turbopump of a staged combustion cycle based rocket engine has been improved by incorporating the large backward leading edge sweep. It has also been found out that the inducer with leading edge sweep work satisfactorily under design and off-design cavitating conditions for the throttling range varying from 60% to 105% with increased stall margin with stall occurs below 80% of the nominal thrust value. It has been elucidate that the inducer with large leading edge sweep have lower efficiency.
2. However, there are some compromises in terms of efficiency at design point and NPSHA albeit to a little extent making it more prone to cavitation.

3. It has also been observed that the nature of cavitation has been changed from tip cavitation to attached or fixed cavitation with the incorporation of leading edge sweep.

From the above observation it is concluded that inducer with leading edge sweep is the viable option for a booster turbopump for a high pressure ratio staged combustion cycle based rocket engine.

**Nomenclature**

- \( p_{o,2} \): Stationary frame total absolute pressure at the inducer exit [MPa]
- \( p_{s,2} \): Absolute static pressure at the inducer exit [MPa]
- \( \rho \): LOX density = 1141 [kg/m\(^3\)]
- \( H \): Total head developed [m]
- \( H = \frac{p_{s,2} - p_{s,1}}{\rho \times g} \)
- \( Q \): Volumetric flow rate [m\(^3\)/s]
- \( Q = \frac{\text{massflowrate}}{\rho} \)
- \( N_d \): Designed rotational speed [rpm]
- \( N_s \): Specific speed
- \( N_{\psi} \): Total head rise coefficient
- \( \psi_s \): Static head rise coefficient
- \( \sigma_{\text{cav}} \): Inlet cavitation number
- \( \sigma_c \): Thoma cavitation factor
- \( \phi \): Flow coefficient at the inducer tip
- \( \eta_p \): Efficiency from power = \( \frac{P_t}{P_h} \)

**Subscripts**

- \( d \): Design point; \( 1 \): Inducer inlet; \( 2 \): Inducer outlet; \( o \): Total; \( s \): Static

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