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AERODYNAMIC ANALYSIS OF AN ARROW WITH DIFFERENT FLETCH CONFIGURATIONS: A COMPUTATIONAL APPROACH

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Abstract:

Archery is being contemplated for hundreds of years; however, there have been not many investigations expressing and clarifying the optimal design and aerodynamic effectiveness of an Arrow. Presently Archery has turned into a significant game in Olympics. Every nation is showing colossal interest in delivering champions. So, it is important to work on the solidness of the Arrow to such an extent that its precision and aerodynamic characteristics improve. A broad examination is proceeding to work on the streamlined exhibition of the Arrow. So, this study intends to explore the aerodynamic characteristics of an Arrow for various fletches and diverse Arrow points. To accomplish this, the initial trends of aerodynamics characterization were obtained by XFLR5 v6.51, and then deep flow analysis was performed by Computational Fluid Dynamics using ANSYS Fluent. The outcomes are upon to show that the Arrow performs better at a speed range of 40-60 m/s and angles of attack from - 5 to +5 degrees. MATLAB is employed in plotting all of the non-dimensional data fluctuations since it is the most trusted plotting software. The outcomes are validated with existing research work and significant conclusions are obtained.

Keywords: Arrow; Fletches; Stability; Archery; XFLR5

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1. INTRODUCTION:

Aiming the arrow at the bullseye and succeeding at it is the only dream of any archer. In the endeavour, designing an Arrow is of utmost priority. An Arrow constitutes of many parts, viz. the point (arrowhead), the nock (aftmost part of an arrow), the shaft, and the fletching [1,2], most of which don't have a major effect on stability. But the fletching plays a crucial role in providing longitudinal static stability. A considerable measure of static stability is needed for the Arrow, to attain the greatest accuracy. So, articulating the structural design of an Arrow facilitates us to understand its behaviour immediately after its release from the bow. Modern Arrows are manufactured from lightweight materials such as carbon fibre, aluminium, fibreglass, and timber wood which are meant to have the least impact on detouring the arrow from the desired trajectory. Since static stability is a vital parameter, fletches play the most critical part in stabilizing by developing aerodynamic forces which create a stabilizing moment around the centre of gravity of the whole Arrow body. For an instance, Helical or spiral fletching helps in increasing the accuracy by the virtue of induced rotation to the arrow [3]. This moment depends upon the aerodynamic structure of the fletch, centre of gravity along with the angle of attack (in particular, ballistic approach).

Initial wind tunnel investigations performed on the aerodynamics of arrows [4] emphasized the effect of fletching on drag production. It is observed that fletching imparts approximately

40% of the total drag [5,6]. The aerodynamic structure of a missile seems just like that of an Arrow; however, the most important difference is that the former has its very own propulsion system to produce thrust and the latter has mere initial thrust throughout the journey. Due to drag, the relative velocity of the Arrow decreases with respect to time. Reynolds number plays a major role in inducing the drag, as drag is directly proportional to Reynolds number [7].

For a short duration, the change in velocity is considered as zero, so stability analysis for constant velocity in XFLR5 v6.51. Some assumptions are made to carry out the evaluation, minimizing any errors viz. consideration of a non-viscous flow and restriction of vibrations all along the trajectory of the Arrow.

This paper enables us to analyze the modifications in the geometric parameters that affect the static stability of an Arrow (with the change in the angle of attack in addition to the dimensions of a fletch).

There are many studies on the arrow which assist in locating the angle of attack at which flow separates using wind tunnel and water tunnel tests [8]. Aerodynamic analysis was done by creating a circular magnetic field around the test section of the wind tunnel and hovering the metallic Arrow at the centre of the magnetic field [5].

As the stability analysis of an Arrow is similar to that of an aircraft, the following equations of motion apply to both cases [9].

$$m(\dot{u} + qw - rv) + mg\ sin\theta = X \quad (1)$$
$$m(\dot{v} + ru - pw) - mg\ cos\theta\ sin\emptyset = Y \quad (2)$$
$$m(\dot{w} + pv - qu) - mg\ cos\theta\ cos\emptyset = Z \quad (3)$$
$$I_{XX}\dot{p} - I_{XZ}\dot{r} + (I_{ZZ} - I_{YY})qr - I_{XZ}pq = L \quad (4)$$
$$I_{YY}\dot{q} + (I_{XX} - I_{ZZ})rq + I_{XZ}(p^2 - r^2) = M \quad (5)$$
$$-I_{XZ}\dot{p} + I_{ZZ}\dot{r} + (I_{YY} - I_{XX})pq + I_{XZ}qr = N \quad (6)$$

The above equations are with respect to the inertial axis system which is Earth's axis system. In the above equations, Eq. No. 1, 2, 3, represent the three force equations and Eq. No. 4, 5, 6 represent moment equations of motion for an aircraft that is symmetrical along the XZ plane, therefore the moment of inertia along XY and YZ planes is equal to zero. In the above equations "m" is the mass of the aircraft $\dot{u}$, $\dot{v}$, $\dot{w}$, are the rate of change of velocities in the X, Y, Z axis in the body axis system. $\Psi, \theta, \emptyset$ are Euler angles.

For the straight-line trajectory and range of an Arrow, the body stability of the archer is extremely important as studied by Bruce R. Manson [10]. Since we can relate the performance of Arrow with the missile, on decreasing the diameter of the missile, drag decreases [11], so it can be concluded that the diameter of the shaft also plays a vital role in producing drag. It can also be stated that fletch dimensions also create the drag, which influences the aerodynamic performance. Many types of Arrowheads such as 3D, bullet, cone-shaped were considered for experimentation on drag analysis which showed that the average drag force is comparatively less in the case of the cone-shaped head [12]. According to the analysis done by Nenad Vidanović on missiles, for the missiles with an initial fin area of 0.5025 m^2, there is an 11.64% improvement in the performance of the missile on increasing the fin area to 0.561 m^2 [13]. For a missile or an arrow, there is a conventional drawback to the rotation of the shaft. If the shaft rotates there will be Magnus and gyroscopic effects, which alter the trajectory of an Arrow, which results in decreasing the probability of hitting the target [14]. Till now many researchers focused on spinning missiles and controlling their trajectory by external means [15]. But in the case of Arrow, there is no external propulsion system that rectifies the deviation created by the gyroscopic or Magnus effect. So, Arrow should be controlled without rotating, which is not feasible in a real-life scenario. So, archers take the advantage of this deviation to counteract any local gust effects.

Till now there is no research based on the effect of the height of fletches on the performance of an Arrow. There is hardly any research on finding the effect of the fletch height on the stability of an arrow which is going to be presented in this paper. For the first time, a study of an Arrow is done using XFLR5 software to study the factors providing aerodynamic stability more simply.

2. COMPUTATIONAL ANALYSIS :

2.1. Designing an arrow in XFLR5:

To have superior accuracy and static stability for an arrow, one must study the variation of the pitching moment with the change in angle of attack. The lift force that is created at fletches due to the variable angle of attack plays a major role in creating the moment around the centre of gravity. XFLR5(X-Foil Low Reynolds number) is open-source software that helps in providing the report of the required parameters. This software is used to study flow specifically at low Reynolds numbers with the aid of three main techniques for the analysis, namely lifting line theory, vortex lattice technique, and 3D panel approach.

The main complication while designing the arrow in XFLR5 software is that we need to modify the aircraft dimensional parameters such that it acquires the shape of an arrow. The aircraft that is pre-defined in XFLR5 software is shown in Figure 1, and the arrow created by changing the aeroplane's dimensions is shown in Figure 2.

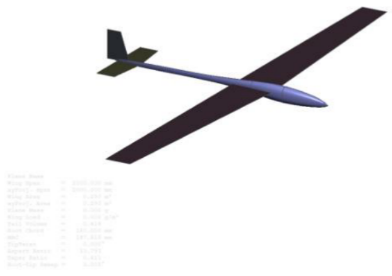

Figure 1. Default model displayed in XFLR5.

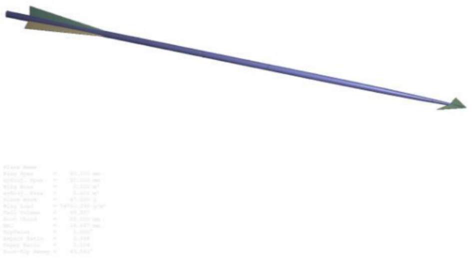

Figure 2. Arrow after modifying dimensional parameters.

To create the shaft of an Arrow from the fuselage, the BSplines type is selected to create a perfect circular cross-section. Seven panels are selected at a distance of 0 mm, 50 mm, 300 mm, 400 mm, 500 mm, 600 mm, 700 mm respectively from the origin. In the first panel, all the frames are set to 0 mm to make the pointed edge. The dimensions of the main wing are modified such that it resembles the arrowhead of the conventional Arrow. Arrowhead is made such that the span is 50 mm in length and the offset between the root and tip of the head is 30 mm. These are the imprecise dimensions of the conventional Arrow. To make the tail part of the aircraft look like the tail of an Arrow, each fletch must be mutually inclined at 120° . For this, the horizontal tail is made 30° anhedral, so that it resembles three fletched arrow tail. For all the aerodynamic parts of the Arrow, like arrowhead and fletches, NACA0002 aerofoil is used. The reason for using NACA0002 aerofoil lies in the conventional thickness of the fletch (to be precise it is the maximum thickness of the root chord of the fletch) it is 2mm. Considering our chord length, it is found that 2 percent of chord length gives optimal aerofoil. We might notice that NACA0002 is a symmetrical aerofoil, this is chosen because the conventional fletch system has symmetrical fletches. All the dimensions of the Arrow are provided in table 1. To get the absolute clarity of the dimensions of the Arrow, the CATIA model is made, shown in Figure 3.

The weights of arrow parts are given below:

Head weight: 9 grams

Shaft weight: 30 grams

Fletches weight: 3 x 2 grams

Table 1. Dimensions of the modelled arrow.

Arrow part	**Dimension**
Length	700 mm
Diameter	4 mm
Head	30 mm
Fletch Length	150 mm
Fletch Height	16 mm, 17 mm, 18 mm

The analysis is done by varying the angles of attacks from -5° to +5°. For the analysis, a fixed airspeed of 60 m/s is considered and the Horseshoe vortex analysis method under Body panels is employed. The horseshoe vortex model helps in representing the vortex system as it describes the pattern of flow that is created by the fluid. In XFLR5, the density of air is taken as 1.225 kg/m^3 by default. The complete analysis is done by changing the angles of attacks and graphs are plotted between the required parameters using MATLAB for the verification of stability of the arrow.

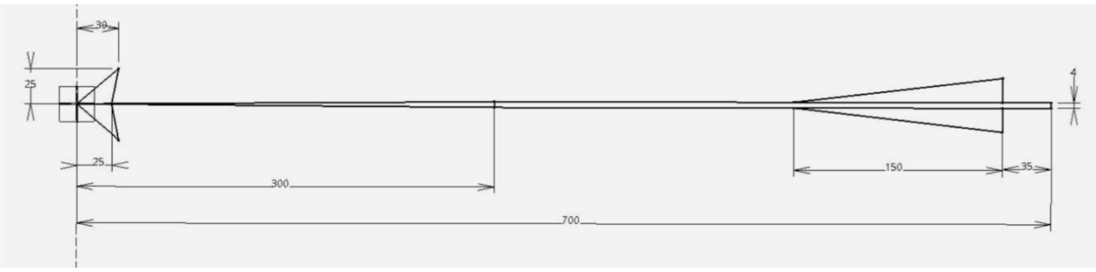

Figure 3. CATIA model of the arrow.

2.2. Flow analysis using ANSYS:

To perform the analysis in the ANSYS software, the CATIA model of the arrow is made and imported into the design modular in ANSYS Fluent. CATIA model is designed congruent to the XFLR5 model to perform a comparative analysis.

2.2.1. Preparation of CATIA Model: A circular shaft of length 700 mm is created with a pointed end at the one end of the shaft. The diameter of the shaft is taken as 4 mm. For the construction of the fletches, NACA0002 aerofoil coordinates are imported into the CATIA software, and using the multi-section solid tool the aerofoil is joined to a point at a distance equal to the height of the fletch. Fletches are assembled with the shaft that is created at the offset of 120º from the distance of 35 mm from the rear end.

2.2.2. Analysis in ANSYS FLUENT: The arrow model was imported into Design Modeller. The imported model is scaled down by a factor of 5. An enclosure of dimensions 163 mm x 24.5 mm x 25.196 mm is generated around the arrow to initialize the control volume. Boolean operation is performed to remove the volume of the scaled arrow from the control volume. The sections of the control volume are named Inlet, Outlet, for the front and back faces respectively and Walls for all the four remaining side faces.

An unstructured quadrilateral mesh was generated for the model since the geometry is complex. For the arrow, a face meshing is of element size 0.05 mm is generated as it needs to be refined. A growth rate of 1.2 is set for the mesh. For the inlet, laminar flow of velocity 60 m/s is set, since the study conducted in the XFLR5 software is also for the 60 m/s velocity, the walls are set to be stationary. For the analysis 100 iterations are performed to examine the velocity and pressure counters at fletches.

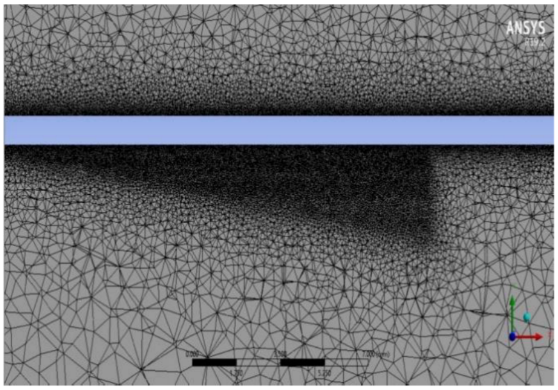

Figure 4. The meshing of the arrow fletch.

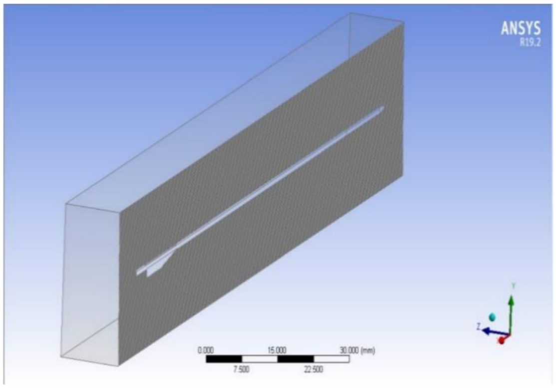

Figure 5. Sectioned view of the Boolean.

3. RESULTS AND DISCUSSION:

For the stability of an arrow, certain parameters should be concentrated, they are coefficient of drag (CD), coefficient of lift (CL), and coefficient of pitching moment (Cm). In this analysis, the standard height of the fletch is considered as 17 mm and the root chord length 150 mm. As a consequence, the standard h/c (height to chord length ratio) value is equal to 0.11. Following are the comparisons for the variation of parameters with the 7% positive and negative variation in height of fletches.

3.1. VARIATION OF COEFFICIENT OF DRAG WITH ANGLE OF ATTACK

In general, the flow is considered inviscid in XFLR5 software, for this reason, there is no effect of parasite drag (form drag and friction drag). So, the only constituent for the coefficient of drag (CD) is Lift Induced drag. Figure 6 portrays the change in the coefficient of drag with respect to the change in angle of attack (α). As the height increases, the drag increases with the change in angles of attack. This represents that the induced drag increases with an increase in the angle of attack and the rate of change of coefficient of drag (slope of the graph) increase with the increase in fletch height.

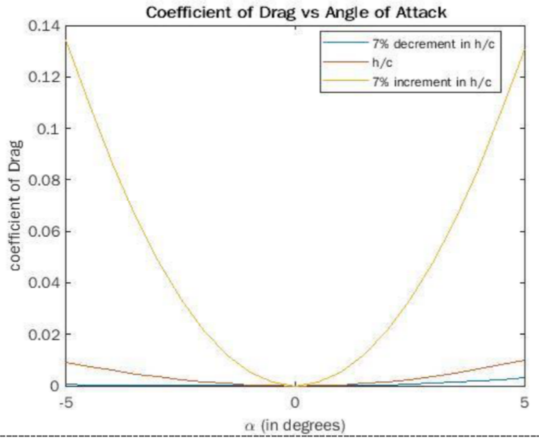

Figure 6. Coefficient of Drag Vs Angle of attack

3.2. VARIATION OF COEFFICIENT OF LIFT WITH ANGLE OF ATTACK:

Figure 7 shows the change in the coefficient of lift (CL) with the change in angle of attack (α) for the various heights of fletches. As we know that the lift force acting on the surface is directly proportional to the surface area. As a result, on the increase in the height of fletch, the surface area increases, as a consequence the lift force increases. This depicts that, on the increase in the fletch height the coefficient of lift increases.

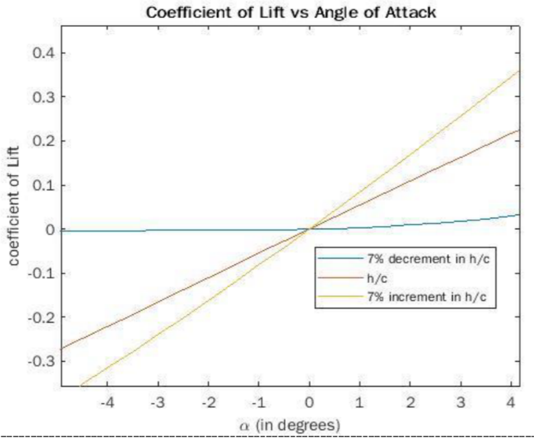

Figure 7. Coefficient of Lift Vs Angle of attack

3.3. VARIATION OF COEFFICIENT OF PITCHING MOMENT WITH ANGLE OF ATTACK:

For the longitudinal static stability of an Arrow, the moment that is created by the lift force at fletches around the centre of gravity is considered as the pitching moment. Figure 8 shows the variation of coefficient of pitching moment with the change in angles of attack for various fletch heights. We can inspect that as the angle of attack increases, the coefficient of pitching moment increases. This results in stabilization of the Arrow (longitudinal static stability), provided that the deviation in the angle of attack is small.

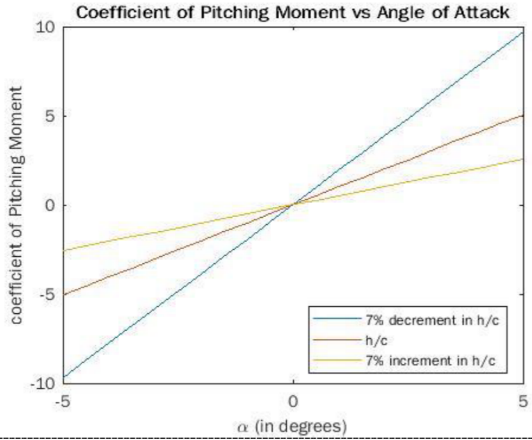

Figure 8. Coefficient of Pitching Moment Vs Angle of attack

3.4. ANSYS ANALYSIS:

The study done by the ANSYS helped in visualizing the pressure and velocity contours aft of the fletch. This helps in validating the analysis done by the XFLR5 for the understanding of stability parameters. Figures 9 and 10 depict the pressure and velocity contours of the arrow respectively.

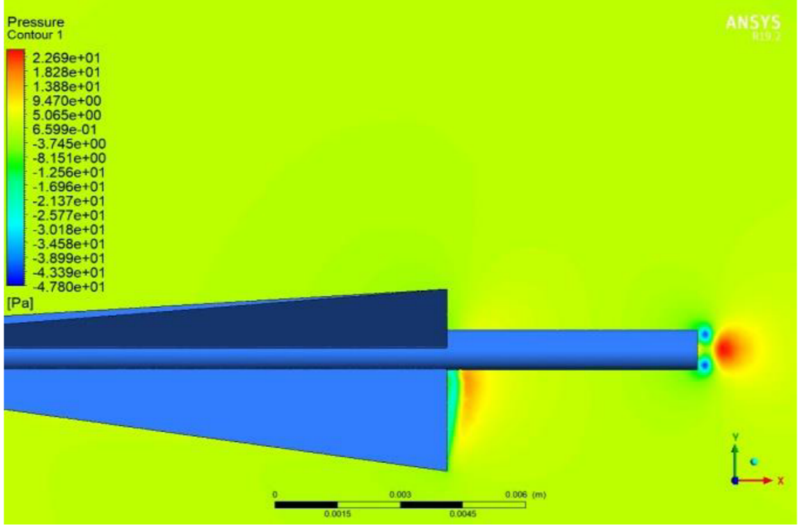

Figure 9. Pressure contour aft fletches.

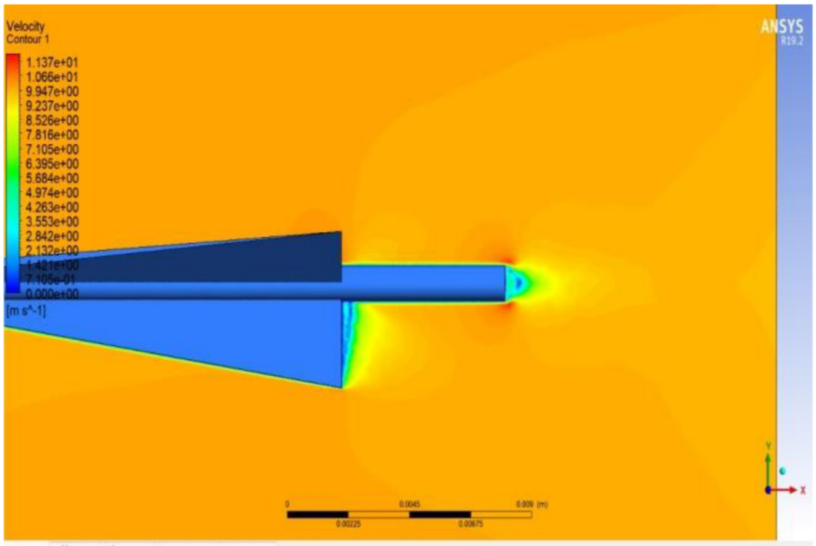

Figure 10. Velocity Contour aft Fletches.

4. CONCLUSION:

This analysis, however, is likely to be less optimum providing only trends of aerodynamic characteristics but not accurate results and can be used for future references and helps in understanding the role of fletches in the stability of an arrow. The arrow showed a noticeable change in the aerodynamic characteristics and it did satisfy many theoretical properties concerning change in angle of attack.

Considering the pitching moment helps stabilise the longitudinal deflection that may be caused by a gust or due to the little deviation while releasing the arrow from the bow. The graph that is plotted between the coefficient of pitching moment and angle of attack clearly describes that on increasing the height of fletch the stabilizing effect of the Arrow increases which is the greatest advantage for any archer. As the lift force at the tail increases the moment that is created for stabilizing the arrow increases.

A very serious point is made by Cm Vs α and CL Vs α plots that increment in height of fletches increases lift produced. Excess lift affects the straight-line trajectory of the Arrow. So, it's far advised to adjust the height of fletches for more stability which emphasizes the trade-off amidst stability and straight-line trajectory of an Arrow.

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