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DEVELOPMENT AND ANALYSIS OF ARROW FOR ARCHERY

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ABSTRACT

This project is about the development and analysis of arrow for archery. 3 types of arrow head been designed: bullet shaped head, 3D shaped head and cone shaped head. The arrow performance measurement parameters were studied such as the FOC values, static stiffness values and the drag forces. SolidWorks 2012 was used to designs the three types of arrow head and the drag force is simulated by using SolidWork Flow Simulation. The material used for the arrow head fabrication is stainless steel 304. The arrow shafts used are carbon shaft of 5.46mm outer diameter and 7mm fiberglass and carbon fiber shaft. 3 different shaft properties are used to determine the effect of static stiffness, arrow heads weight and shaft diameter on the drag force generated at the arrow. The experimented result for Beman 570-14 arrows are slightly higher compared to simulation results obtained from Solid Works. The possible cause is the characteristic of the arrow during flight where arrows starts to bend in C manner then straight again then bend again in reverse C manner and so on when it been shot. These deformation causes energy losses to the surrounding due to air friction, natural damping effect and shear friction. From the result obtained, it is shown that fiberglass shaft arrow has the highest drag force regardless of the arrow head types used compared to the other two types of shaft. Although Beman 570-14 shaft has smaller frontal area compared to a 7mm outer diameter carbon fiber shaft, the drag force obtained from the experiment shows that both bullet shaped head and 3D shaped head for carbon fiber shaft has lower drag force compared with the same arrow head shape.

Keywords: archery, arrow head, drag force, static stiffness.

INTRODUCTION

Archery has been used for centuries to hunt and combat. In the modern day, archery main uses are for sport and hunting. From the mid of 19 century, the attempt to turn archery as modern sport has been done and now it is even an official Olympic games. Since then, the factors that help to promote better shooting accuracy has been investigated scientifically. Archery equipment performance is divided into: 1) the performance of the bow launching the arrow; 2) the performance of the arrow in flight; and 3) for bowhunters, the performance of the arrow-broadhead combination on impact (Barton *et al.,* 2012).

In archery especially for sport, the performances not only rely on the bow design and characteristics. Instead, arrow design and parameter also play an important rule and has a major effect on archery accuracy and precision. There is only a few scientific studies are known on the aerodynamic properties of an arrow, although they have dominant effects on down-range velocity and also on its drift in wind (Okawa, Komori, Miyazaki, Taguchi, and Sugiura, 2013). Currently, most of the current investigation is carried out to determine certain current market arrow without designing the arrow and try to improve it. The scope of previous investigation mostly limits on the mechanics of arrow flight upon release, the interaction between bow and arrow, and measurement of arrow drag in a tunnel. Without the investigating the velocity and trajectory of the arrow.

In archery, both bow and arrow play an important roles in creating a stable, accurate and desired shooting range. Arrows are made from stiff and low density material such as wood, fibre glass, aluminium, carbon fibre, and composite of carbon fibre and aluminium which can be either rods or tubes shaft. A good arrows must be able to bend at certain degree as the arrow will not be able to shot if the shaft is too stiff (Leach, 2014). A higher speed arrow able to remain their flight better. All the parts of arrow play an important role in providing the arrow speed as well as the flight stability. The main parameter influencing the arrow behaviour during flight are: 1) weight of arrow tip; 2) arrow spine and 3) fletching type (Barton *et al.*, 2011).

The common materials used for arrow head are stainless steel, bronze, tungsten and aluminium. There are two parameters of the arrow head that affect the arrow flight: arrow head weight and type of arrow head. Arrow head in market comes with various weights ranging around 75gr to 125gr.

Higher arrow weight result in higher Front of Center (FOC) which allow better flight but the flight range was sacrificed. Modern arrows also come with wide range of arrow head type. The aerodynamic properties of the arrow head influence the drag force on the arrow. The drag coefficient of bullet point and bluff bodied is significantly larger than streamlined point (Mukaiyama, Suzuki, Miyazaki, and Sawada, 2011).

Arrow shaft also play an important role in giving a stable arrow flight. The common shaft materials are carbon, aluminium, fiberglass and wood (Barton *et al.*, 2011). The characteristics of an arrow shaft that affect the flight behaviour is the weight and stiffness. Both parameters greatly depend on the shaft design and the material of shaft. Carbon shaft provide a stiff and lighter shaft compare to aluminium which enable a lighter and more aerodynamic shaft construction. Currently, composite of carbon and aluminium is the optimum design for an arrow shaft. A correct arrow spine help to ensure the arrow neither bend too much creating a whippy arrow or too little creating a stiff arrow (Elliot, 2002).The arrow

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spine was evaluated through static arrow spine and dynamic arrow spine. Static spine is the measurement of shaft deflection by supporting the arrow at two point separated for 28 inches apart and suspend a weight of 1.94 lb at the middle. Static arrow spine is determined by the shaft geometry and material elasticity. The geometry of the shaft such as the cross section shape, the diameter and material bonding has a great contribution in static arrow spine. According to the archery rule, the shaft diameter needs to be less than 9.3mm.

A projectile's flight is at the most stable state when the projectile's mass is positioned at the Front of Center (FOC). FOC is the position where the balance between stability and range situated. The range of FOC recommended for varies archery are: 11% to 16% for FITA (Olympic style), 6% to 12% for 3-D archery, 10% to 15% for field archery and 10% to 15% for hunting (Ashby, 2005). Arrow will wobble when the FOC is near to its center (Archery, 2008). The standard FOC calculation was based on Archery Manufacturer Organization (AMO) standard formula was expressed as in Equation. (1)

FOC = [(arrow balance point/ total arrow length)-.50] x 100 (1)

Arrow will turn round and fly backward if the center of drag is in front of the center of mass (Leach, 2104). Larger mass at the arrow tip caused the shaft to deform more (inertia effect) which is the same as decreasing shaft stiffness (Lieu, Kim, and Kim).

Arrow performance is crucial for target archery. The main parameter that determine an arrow performance is the arrow flight pattern, arrow velocity and arrow trajectory. In real flight situation, few methods such as in-flight ballistic measurement system, high speed video recording, ballistic chronographs and acoustic Doppler shift are used to measure arrow performance. In general, arrow performance can be evaluated by measuring the arrow drag as instable arrow flight will increase the arrow drag (Barton *et al.*, 2012).

However, a cheaper way to determine an arrow drag is the use of high speed video camera to record the arrow during free flight. According to Miyazaki *et al.* (2013) in their experiment, two high speed camera was placed 45m apart and velocity decay rate is used to determine the drag coefficient. The arrangement used by Miyazaki *et al.* (2013) in their experiment set up is as shown in Figure-1.

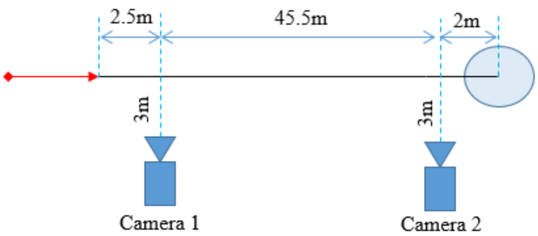

Figure-1. Experiment set up.

METHODOLOGY

Concept generation of arrow head will be divided into three categories: bullet-shaped point, 3D-shaped point and cone-shaped point. The results are obtained by using Solidwork Flow Simulation 2012. The computational domain used to analyse the arrow drag force is 3D simulation. The arrowheads were designed according to the dimension of Beman 570-14 carbon arrow shaft outer and inner diameter of 5.46mm and 3.76mm respectively and 7mm outer diameter with 5mm inner diameter shaft. The arrowhead weight is designed to be 5.10 gram for Beman shaft and 8.1 gram for 7mm shaft. The dimension of the computational domain is shown in Table 1 and the domain is as illustrated in Figure-2. There are several parameter been set during the flow analysis. Table-1 shows the parameter been set before running the flow analysis.

Table-1. Parameter used for flow analysis.

Velocity (m/s)	**60**
Gravitational acceleration (m/s^2)	9.81
Fluid type	Air
Computational domain (m)	1.5 (L) X 0.14 (W) X 0.22 (H)

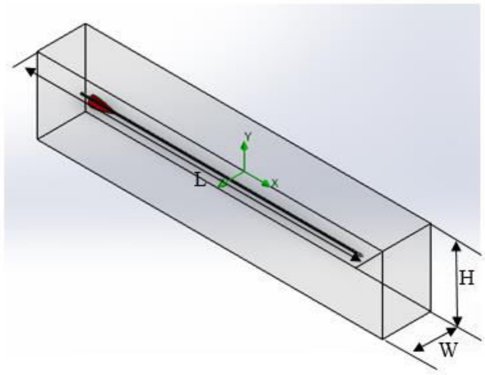

Figure-2. Computational domain used to analyse arrow drag force.

Figure-3, Figure-4 and Figure-5 show the result from Solidworks Flow Simulation base on the parameter been set as shown in Table-1 and Figure-2. Table-2 shows the drag force value obtained.

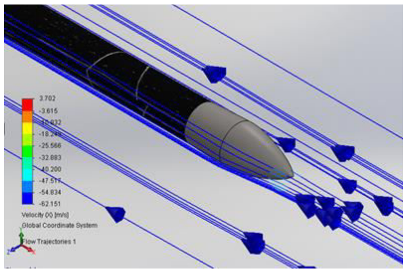

Figure-3. Result for bullet shape head.

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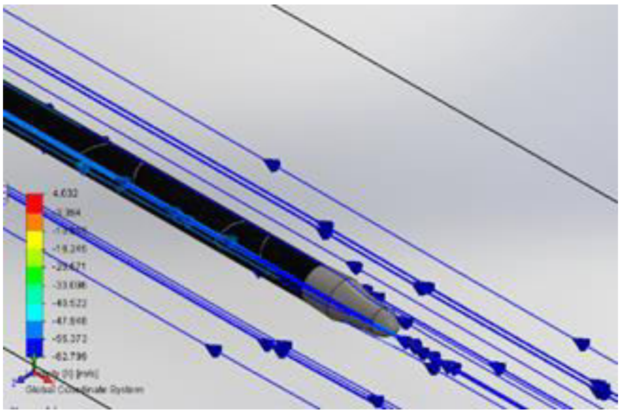

Figure-4. Result for 3D shaped head.

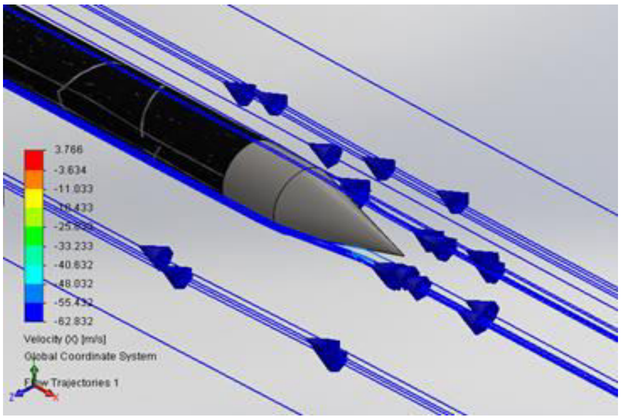

Figure-5. Result for cone shaped head.

Table-2. Arrow head drag force.

Point	Averaged drag force (N)
3D shaped 3	0.1176
Bullet shaped 3	0.1139
Cone shaped 1	0.1088

The arrow head was fabricated from stainless steel type 304 by using CNC lathe machine. Stainless steel type 304 is used as it is the most flexible and widely used stainless steel type which make it easily available. Three types of arrow head was fabricated which is the 3D-shaped, cone-shaped and bullet-shaped as shown in Figure-6.

Figure-6. Fabricated arrow head.

A test rig as shown in Figure-7 was designed and fabricated by using 3D printing. A mild steel solid rod with the weight of 880gram was hanged at the middle of the test rig as the load to determine the deflection of the tested shaft. The deflection value of the shaft was measured by using Vernier calliper. The deflection value was tabulated as shown in Table-3.

Table-3. Static spine stiffness according to type of shaft.

Shaft	Beman 570-14	Fiberglass	Carbon fibre
Diameter	5.47	7	7
Spine stiffness, mm	16.58	18.94	6.08
	16.54	19.5	6.08
	16.6	19.2	5.34
Average, mm	16.57	19.21	5.83

Figure-7. Test rig for arrow shaft.

To analyse arrow drag force by using high speed camera, there are two main parameters need to be know: video recording frame rate used and the arrangement of the cameras. In this experiment, the method used to determine the arrow drag force is by determining the velocity decay rate has been conducted by Miyazaki *et al.* (2013). The video recording frame rate used will be 240 fps which is the maximum frame rate for Casio Exilim HS EX-ZR500 digital camera. The bow used for the arrow shooting is Hoyt Pro Comp Elite as shown in Figure-8. Hoyt Pro Comp Elite is a compound type bow. Compound bow is used for the shooting of arrows it has higher launching efficiency thus minimizing the error during shooting. This will able to provide a more accurate data.

Figure-8. Hoyt Pro comp elite.

The determination of drag coefficient was by using Equation. (2), the velocity decay rate need to be determined by using Equation. (3) have been proposed by Miyazaki *et al.* (2013).

$$C_D = \frac{4m_a\widehat{D}}{\rho\pi D^2} \tag{2}$$

$$\widehat{D} = -\frac{2}{s}\ln\left(\frac{U_2}{U_1}\right) \tag{3}$$

RESULTS AND DISCUSSIONS

The properties and parameters for all the arrows are tabulated in Table-4. All these parameters are important for the result analysis.

Table-4. Parameter for each arrows according to shaft and head types.

Arrow	FOC, %	Spine stiffness, mm
5.46mm carbon shaft:		
Original head	6.2883	16.57
Bullet shaped head	6.4417	16.57
3D shaped head	6.1350	16.57
Cone shaped head	6.1350	16.57
7mm fiberglass shaft:		
Bullet shaped head	7.3620	19.21
3D shaped head	7.3620	19.21
Cone shaped head	7.3620	19.21
7mm carbon fiber shaft:		
Bullet shaped head	9.0491	5.83
3D shaped head	9.0491	5.83
Cone shaped head	9.2025	5.83

From Table-4, 7mm carbon fiber shafts have the lower spine stiffness showing that these shaft is stiffer compared to 7mm fiberglass shaft and Beman 570-14 (5.46mm carbon shaft). In overall, all the arrows have a constant FOC ranging from 6% to 10%. In order to determine the drag force, the drag coefficient need to be determined beforehand by using both Equation. (2) and Equation. (3). The iron rule is that higher drag coefficient value creates higher drag force on the arrow. This causes higher velocity drop across the distances.

The velocity for the arrow and the angle of the arrow velocity was determined by using Kinovea software. For every types of arrow, 6 values were taken from the video analysis in order to minimize the error in result obtained. The velocity and the angle was tabulated according to the type of arrow shaft namely Beman 570-14, 7mm fiberglass and 7mm carbon fiber.

Beman 570-14

Beman 570-14 is a carbon shaft with 5.46mm outer diameter. 4 type of heads were tested and analysed in order to compare the designed arrow head drag force with the original arrow head which comes together with the shaft. Excluding the arrow head geometry, all the other parameters of the arrows were remained unchanged. The drag coefficient and drag force for all the 4 arrows were tabulated in Table-5.

Table-5. Drag coefficient and drag force for Beman 570-14 arrows.

Head	Drag coefficient, C_D	Drag force, N
Bullet	0.9055	0.0942
	0.8865	0.0990
	1.2811	0.1071
	4.5647	0.3484
	2.7252	0.2355
	1.9394	0.1484
Cone	2.3237	0.1507
	1.7887	0.1361
	2.0258	0.1413
	2.3770	0.1573
	1.7613	0.1454
	1.5789	0.1263
3D	1.9484	0.1696
	2.0336	0.1391
	1.5584	0.1047
	1.9234	0.1401
	1.6358	0.1232
	2.1125	0.1361
Original head	2.5293	0.1719
	2.0185	0.1443
	1.1478	0.0831
	5.3230	0.3496
	4.4038	0.3030
	2.8852	0.2026

The drag coefficients and drag forces obtained is averaged and tabulated in Table-6. The result which has huge different such as the original head result in Table-5 with the value of 5.3230 and 4.4038 drag coefficient is neglected when calculating for the average value as it is too large compared to other value which is around 1.1 to 2.9. It is believed that these result deviates from other result too much due to error in analysis and the state of oscillation of the arrow during flight which create inaccurate result been read by the video analysis software.

Table-6. Averaged drag coefficient and drag force.

Head	Average drag coefficient, C_D	Average drag force, N
Bullet	1.5475	0.1339
Cone	1.9759	0.1429
3D	1.8687	0.1355
Original Head	2.1452	0.2422

Table-6 shows that bullet head has the least drag force compared to other arrow heads with 0.1083N less drag force compared to original arrow head. The result shows that both 3D shaped and bullet shaped head has a high potential to replace the original head for long range shooting.

7mm fiberglass shaft arrow

7mm outer diameter fiberglass shaft was attached with 3 types of arrow heads namely bullet shaped head, cone shaped head and 3D shaped head. The drag coefficient and drag force for all the 3 arrows were

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tabulated in Table-7. Table-8 shows the averaged value for both drag coefficient and drag force.

Table-7. Drag coefficient and drag force for 7mm fiberglass shaft.

Head	Drag coefficient, C_D	Drag force, N
Bullet	2.4225	0.3065
	1.8732	0.2560
	1.7339	0.1551
	1.5816	0.1377
	2.6838	0.2152
	2.9445	0.2322
Cone	2.0451	0.2405
	3.8843	0.3329
	3.0735	0.3294
	2.9369	0.3052
	3.0426	0.2672
	6.0291	0.5392
3D	2.5930	0.3814
	2.4083	0.2977
	1.2752	0.1282
	1.8692	0.1926
	2.3221	0.2025
	2.3951	0.2041

Table-8. Averaged drag coefficient and drag force for 7mm fiberglass shaft.

Head	Average drag coefficient, C_D	Average drag force, N
Bullet	2.2066	0.2171
Cone	2.9965	0.2950
3D	2.1438	0.2344

7mm carbon fiber shaft arrow

7mm outer diameter carbon fiber shaft was attached with 3 types of arrow heads namely bullet shaped head, cone shaped head and 3D shaped head. The drag coefficient and drag force for all the 3 arrows were tabulated in Table-9. Table-10 shows the averaged value for both drag coefficient and drag force.

Table-9. Drag coefficient and drag force for 7mm carbon fiber shaft.

Head	Drag coefficient, C_D	Drag force, N
Bullet	0.6046	0.0901
	0.7278	0.1050
	0.9377	0.0865
	0.6446	0.0616
	1.6757	0.1763
	0.9540	0.1012
Cone	1.1018	0.1180
	0.8964	0.1065
	2.6292	0.2737
	4.0069	0.4053
	2.2547	0.2338
	1.5051	0.1560
3D	0.7519	0.1236
	1.0950	0.1719
	0.1991	0.0204
	0.7060	0.0726
	0.5569	0.0592
	0.9110	0.0964

Table-10. Averaged drag coefficient and drag force for 7mm carbon fiber shaft.

Head	Average drag coefficient, C_D	Average drag force, N
Bullet	2.1452	0.2422
Cone	1.5475	0.1339
3D	1.8687	0.1355

Figure-9 shows that experimented result is slightly higher compared to simulation results. The possible cause is the characteristic of the arrow during flight. In real life, arrow will starts to bend in C manner then straight again then bend again in reverse C manner and so on when it been shot. These deformation causes energy losses to the surrounding due to air friction, natural damping effect and shear friction. Thus, it results in higher drag forces compared to simulation results which are under ideal condition.

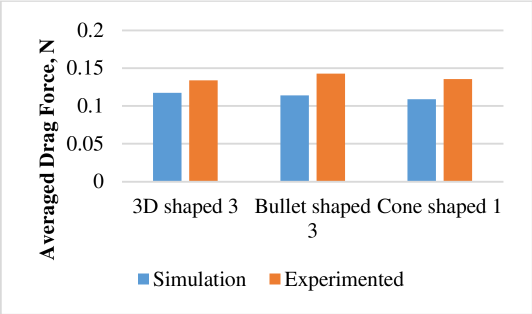

Figure-9. Comparison of simulation and experimented drag force bar chart.

From the bar chart in Figure-10, it shows that fiberglass shaft arrow has higher drag coefficient regardless of the arrow head geometry used. On the other hand, 5.46mm carbon shaft (Beman 570-14) arrow has the second highest drag coefficient for every types of arrow head used. Although carbon shaft has larger diameter of 7mm compared to Beman shaft, it has the lowest drag coefficient for all of the arrow head types used. This is due to the stiffness of the shaft compared to all the other two types of shaft. As the formula used relate velocity decay rate with the drag coefficient, thus, the higher the velocity decay, the higher the drag coefficient value will be.

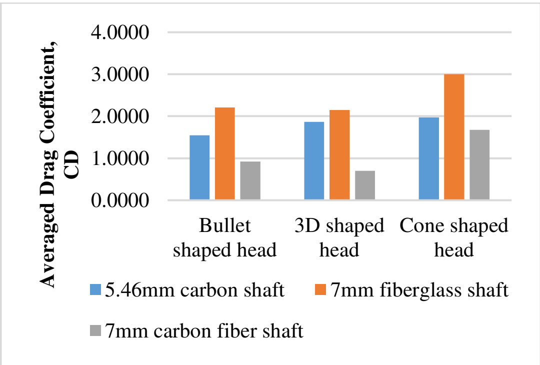

Figure-10. Averaged drag coefficient bar chart.

From the bar chart in Figure-11, it shows that fiberglass shaft arrow has higher drag force regardless of the arrow head geometry used. On the other hand, 5.46mm carbon shaft (Beman 570-14) arrow has the lowest drag force when cone shaped head is used. Although carbon shaft has larger diameter of 7mm compared to Beman shaft, it has the lowest drag force when bullet shaped head and 3D shaped arrow head types used. This is due to the stiffness of the shaft compared to all the other two types of shaft.

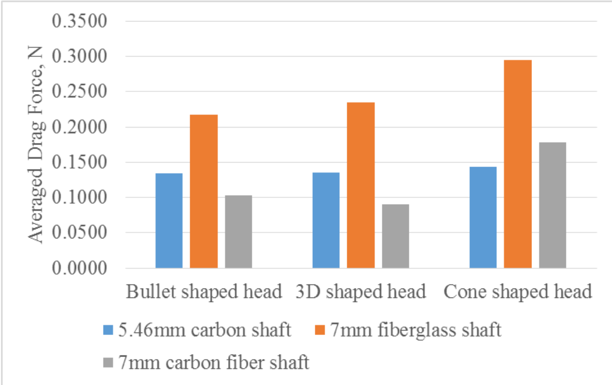

Figure-11. Averaged drag force bar chart.

As the formula used relate velocity decay rate with the drag coefficient, thus, the higher the velocity decay, the higher the drag coefficient value will be.

CONCLUSIONS

From the result obtained, it is shown that fiberglass shaft arrow has the highest drag force regardless of the arrow head types used compared to the other two types of shaft. The result shows that although Beman 570-14 shaft has smaller frontal area compared to a 7mm outer diameter carbon fiber shaft, the drag force obtained from the experiment shows that both bullet shaped head and 3D shaped head for carbon fiber shaft has lower drag force compared with the same arrow head shape. From the experiment for Beman 570-14 arrow, it shows that bullet shaped head has the lowest drag force compared to other head shape under same shaft which is in contrast with the result obtained by simulation showing that the cone shaped head has the lowest drag force.

The recommendations for this project are:

1. Use high speed camera with better resolution and frame rate.
2. Conduct the experiment in indoor which allow a more accurate set up.
3. Conduct in an environment which as bright as possible.
4. Conduct the experiment with different arrow head weight

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