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Ship Hull Appendages: A Case Study

Shiju John
Scientist, Hydrodynamic Research Wing of the Naval Science & Technological Laboratory, India
Md. Kareem Khan
Scientist, Hydrodynamic Research Wing of the Naval Science & Technological Laboratory, India
P C Praveen
Scientists , Hydrodynamic Research Wing of the Naval Science & Technological Laboratory, India
Manu Korulla
Scientist, Hydrodynamic Research Wing of the Naval Science & Technological Laboratory, India
P K Panigrahi
Scientist, Hydrodynamic Research Wing of the Naval Science & Technological Laboratory, India

Abstract:

Hydrodynamic model studies were carried out at Naval Science & Technological Laboratory (NSTL), Vishakhapatnam, India to estimate the resistance contribution of appendages. This paper discusses categorization of ship hull appendages from a hydrodynamic viewpoint. An attempt is made to qualitatively assess the resistance contribution of each of these categories of appendages to the total ship resistance. A relative appraisal of the resistance contribution of appendages on a naval surface combatant, a submarine, a tanker, a container, a dredger and a single screw ship is made to emphasize the large appendage drag on naval ships. Results obtained from hydrodynamic model experiments conducted at High Speed Towing Tank (HSTT) facility at NSTL on a fast displacement hull form used for naval applications (FDHFNA) are discussed at length as a case study. A criterion for rating appendages is proposed.

1.Introduction

The ship's hull is a streamlined body designed to create favourable pressure gradients so that it encounters minimum resistance to forward motion. However, we have to impose on the hull surface certain add-ons so as to improve the controllability and maneuverability, sea-keeping, strength and structural aspects or to fulfil operational requirements. These attachments which alter the flow around the hull are called ship hull appendages. Appendages can also be designed to improve resistance and propulsion characteristics. [1]

Needless to say, the inclusion of appendages will alter the resistance of the ship. The wetted surface area of the appendages causes an increase in the total frictional drag. If the appendages have abrupt curvatures, flow may separate and cause separation drag. Also, as the appendage modifies the flow around the hull it may affect propulsion performance. An appendage such as a wake adaptive fin may improve the wake characteristics of the inflow coming into the propeller, thereby improving the propulsion performance. At the same time, an A-bracket supporting the propeller shaft reduces the flow between the strut arms causing hydrodynamic problems such as wake peaks. Positioning of the appendages has to be optimized for a favourable influence on the flow.

Appendages may also affect the trim, heave and roll motions. Stabilizer fins are appendages used to control roll and pitch motion of ships. These are more often active stabilizers and assist in ride control. Bilge keels which are passive stabilizers also improve the roll stability of ships. Stern wedges/flaps and interceptors are used to control the trim and heave of high speed vessels. In doing so, they primarily reduce the ship resistance and improve overall propulsive efficiency. [2]

Vibration or noise caused by the faulty orientation of an appendage is a matter of concern in ship design. For instance, a pair of fixed fins near the bow is used in some ships to reduce the pitching motion. However their use is limited due to the vibration associated with the flow separation around the fins. At the same time, fixed fins at the stern have long been used to improve the flow and reduce the propeller vibration. Thus, proper knowledge of the effect of a particular appendage at a particular location on the hull is a vital input for the designer.

Thus, the net effect of appendages is thought to bring about the following changes.

- Increase in frictional resistance
- Alteration of flow around the hull

- Alteration of ship motions
- Induced vibration/noise/cavitation

It is highly recommended that some standards be adopted for ensuring the quality of appendage design from all aforementioned perspectives. However, it is difficult to generalise this process as appendages are of different types depending on their requirement and working principle. Thus it would make the picture lucid if we could categorise the appendages based on their functionality. The authors have worked in this direction in section 2.

In the present paper, section 3 highlights the importance of appendage design in the case of a warship. Hydrodynamic model tests on the appended hull model of a fast displacement hull form used for naval applications (FDHFNA) are carried out at HSTT. The results are discussed in a case study in section 4. The use of flow visualization and wake survey techniques in appendage evaluation is illustrated. The resistance contribution of appendage categories is interestingly brought out in this study. A brief discussion is made on the use of energy saving devices for reducing resistance.

In section 5, the authors propose a rating method for appendages which will enable to assess the hydrodynamic quality of the appendage coupled with its functionality. Overall, this paper attempts to emphasize the need to standardise hydrodynamic design for ship hull appendages.

Figure 1: Classification of ship hull appendages

2. Classification Of Appendages

Ship hull appendages can be classified into the following categories from a hydrodynamic viewpoint:

- Maneuvering Aids
- Motion Inhibitors
- Propulsion Aids
- Structural Members
- Operational Aids
- Energy Saving Appendages

Maneuvering Aids are control surfaces which contribute to the controllability of the ship. Examples are rudders, lift generating foils and skegs. Bow thrusters can also be treated as appendages in this category.

Motion Inhibitors are control surfaces such as fin stabilizers and bilge keels. Interceptors, stern wedges/flaps, ventilated foils are also ride control devices and fall into this category.

Propulsion Aids include those appendages which are a part of the propulsion unit of the ship. These include propeller shaft, propeller hub, wake adaptive fins, vortex generators, pod of a podded propeller and the cowl in the case of a pump-jet propulsor. The propeller as a whole is not considered as an appendage because it is the dynamic effect of the propeller blades that generate the thrust to propel the ship ahead. Conveniently, the drag of the propeller blades is accommodated in the propulsion calculations (as C_D in open water calculations). Since the propeller hub contributes consistently to the drag it is treated as an appendage.

Structural Members such as shaft bossing, shaft brackets/struts, rudder posts and struts of foils among others are also appendages. A high percentage of the structural members are for supporting propulsion aids. In many cases, it may be difficult to isolate these two classes. However, for the purpose of providing a clear distinction they are categorized separately.

Operational Aids are those appendages which are fitted to serve the operational requirement of the ship. Examples are sonar domes, underwater cameras and underwater weapon carriers among others.

Energy Saving Appendages are those which are used for reducing the powering requirement of the ship. Bulbous bow is a classic example in this category. Motion inhibitors such as interceptors, stern wedges and flaps also help in reducing the ship powering and may be accounted in this category as well. Vanes fitted ahead of the propeller to reduce fuel consumption are another example. Propeller ducts for thrust gain, pre-swirl stators and rudder bulb fins (Kawasaki)/thrust fins (Hyundai) which improve propulsive efficiency are other examples. Figure 1 elucidates the above classification of appendages.

3.Appendages On Naval Ships

Generally, naval platforms have more appendages as compared to a conventional merchant ship. Appendages such as sonar domes, dynamic positioning systems, 'A' and 'P' brackets, twin propeller shafts, twin rudders and other operational aids seen on a warship call for serious design considerations. Location, alignment and fairing of these appendages are essential in avoiding cavitation, decreased propulsive efficiency, vibration and noise apart from incremental resistance.

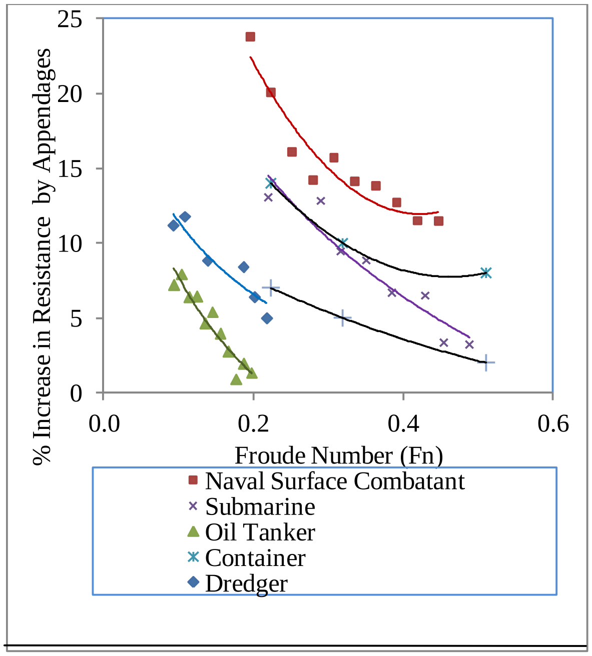

Figure 2: Comparison of appendage resistance for various ship types

A comparison of the appendage resistance of various types of ships is given in Figure 2. Extrapolated full scale data from model resistance tests conducted at HSTT is used for this comparison. It may be seen that the percentage of appendage drag, which is primarily due to frictional resistance and the hull-appendage interaction, is more at lower Froude numbers. The amount of wave making drag also increases with ship speed. This is the reason why the appendage resistance contribution drops down at higher speeds. Model resistance tests are based on the assumption that appendage contribution to wave resistance is nil.

The high percentage of appendage drag on a naval ship is demonstrated in the above comparison. Appendage drag on naval ships generally varies from 20% to 10% across the speed ranges. Case in point hydrodynamic evaluation of the appendages on a similar hull form is presented in Section 4.

4.Case Study

A fast displacement hull form used for naval applications (FDHFNA) is chosen for case study. [3]

4.1.Hull Particulars

The non-dimensionalised particulars of the hull form are as follows:

$L/\Delta^{1/3}$	7.49
L/B	8.57
B/T	3.13
C_B	0.55
Fn_{MAX}	0.42
$Fn_{OPERATION}$	0.25

The list of appendages on this hull form is as follows:

- Bow mounted sonar dome
- Stabilizer fins (2 pairs -P&S)
- Bilge keels (2 pairs - P&S)
- Rudders (P&S)
- Shafts (P&S)
- Cylindrical bossings (P&S)
- 'A' Brackets (P&S)
- 'P' Brackets (P&S)

A scaled down model of the ship with the above appendages was made for hydrodynamic tests at HSTT.

4.2.Flow Visualisation

Bare hull resistance tests were conducted initially. Positioning the sonar dome and its effect on ship resistance was studied using CFD suite SHIPFLOW. A comparison of the pressure profile and total resistance coefficients for different sonar dome locations is given in Figure 3. The bow mounted sonar dome configuration was selected for the present hull form. [4][5]

Flow visualization test was carried out on the bare hull model with bow mounted sonar dome at a model speed corresponding to the maximum speed to visualize the flow over sonar dome and to arrive at the hydrodynamic position of bilge keels & stabilizer fins. The results of the test were examined for specific areas of hull at sonar dome, bilge keel & stabilizer fins location. It was observed that streamlines developed without separation over the bow mounted sonar dome. Over the bilge keel and stabilizer fin locations, the streamlines were running parallel indicating "neutral flow orientation" of these appendages. The streamlines at the "A" bracket strut location were parallel but at "P" bracket the stream lines were inclined to the strut by 10 degrees which may result in considerable flow separation and vibrations. Hence the "P" bracket strut was reoriented to align along the flow as shown in Figure 4. [3]

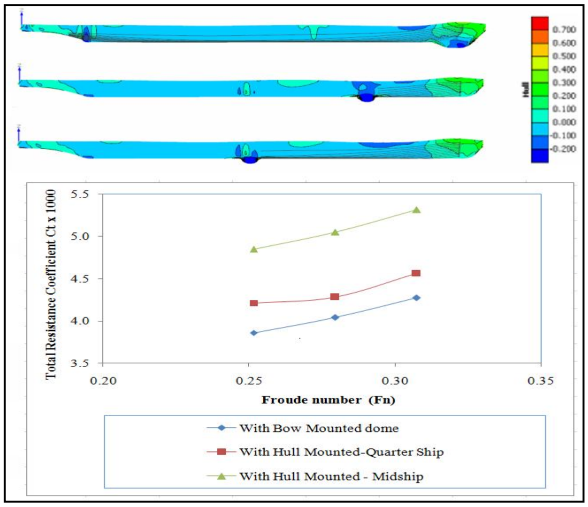

Figure 3: Streamlines and Contours of Static Pressure Coefficient for sonar dome located at bow, quarter ship and midship using SHIPFLOW (top); Comparison of Total Resistance Coefficient (C_T) at Fn = 0.25, 0.30 and 0.35

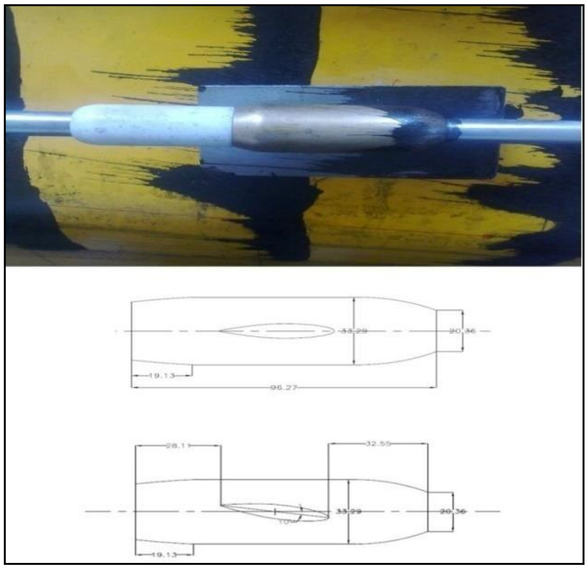

Figure 4: Paint flow results over P bracket indicating 10 deg angle to streamlines (top); Original P bracket design (middle); P bracket realigned by 10 deg after paint flow(bottom)

4.3.Wake Survey

Propeller inflow was examined by carrying out 3D nominal wake survey in the propeller plane at Fn = 0.25 and Fn = 0.42. Results suggested that the inflow to the propeller was distributed properly with uniformly varying velocity ratios, thus ruling out undesired fluctuations in propeller loading. Cutting an arc of about 30° to either side of the top dead centre, a region of wake peak can be seen. This clearly shows the shadow effect of "A" bracket in front of the propeller. The axial iso-wake plot at Fn = 0.42 is reproduced in Figure 5. [6]

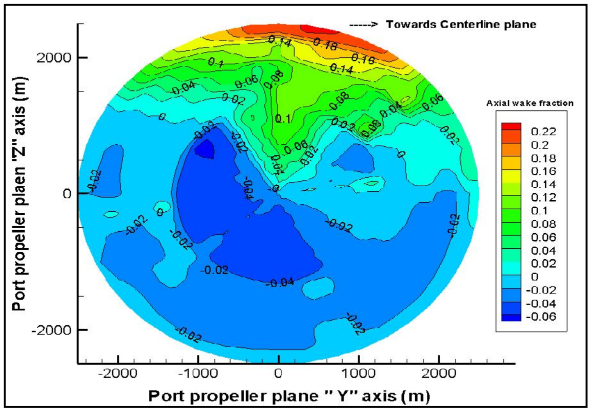

Figure 5: Axial iso wake plot in Port propeller plane at Fn = 0.42

It was observed that the transverse velocity components in the propeller plane are outward dominated. The tangential velocity components were negative in the region of higher wake. To have lowest loading on the propeller while entering this axial wake peak zone, the propeller should have the same direction of the tangential velocity. Thus, for the twin propellers outward rotation was selected. [6]

4.4.Appendage Resistance

Appended hull resistance tests were done in different stages to gauge the resistance contribution of each of these appendages. The percentage increase in resistance created by the appendages is plotted in Figure 6. It may be noted that the bow mounted sonar dome cancels out wave making drag between Froude number ranges of 0.20 to 0.30, thereby reducing total resistance. The marginal hump in the resistance curve which was observed for bare hull resistance tests corresponding to a Froude number of 0.30 was reduced by the bow mounted sonar dome. Overall, it increases resistance by about 2%. The stabilizer fins and the bilge keel increases the resistance at all speed ranges by about 2% and 3% respectively. The propulsive aids and structural members increase resistance by a bigger margin of about 9%. Condition D represents the fully appended hull.

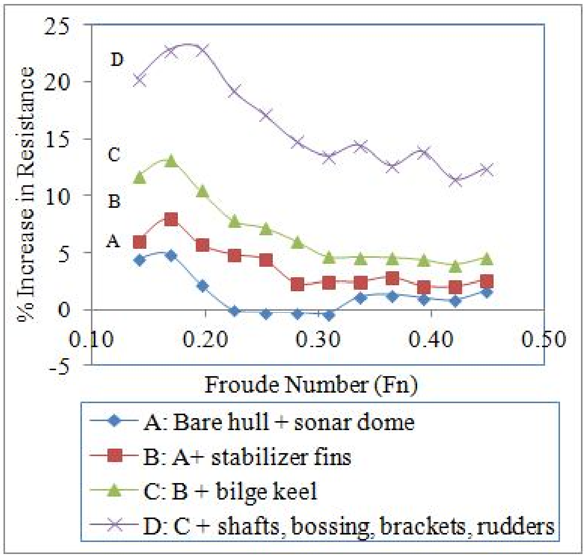

Figure 6:% Increase in resistance by different appendages

4.5.Use Of Energy Saving Appendages

To further reduce the powering requirement, energy saving devices (ESDs) were considered. Stern wedge, flap, wedge-flap combination, interceptor and an innovative wedge-interceptor combination were attempted through a systematic test approach. The best result in each series is plotted in Figure 7. The y-axis represents the ratio of ship resistance with ESDs to that without ESDs. Similar studies in reference [7] suggest that the higher ratios at lower Froude numbers may be due to Reynolds scale effects. On an average, the Delivered Power is brought down by 5% to 10% during self-propulsion tests between Froude number ranges of 0.30 to 0.40. [8]

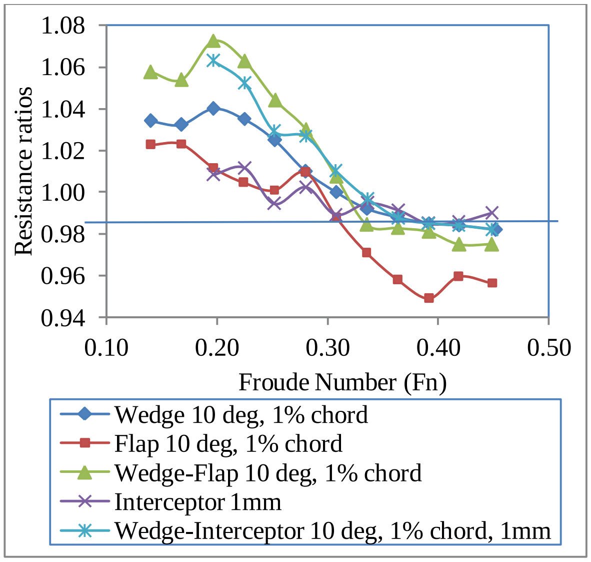

Figure 7: Resistance ratio with Energy Saving Devices

4.6.Resistance Contribution Of Appendage Classes

From this study, the resistance contributions of the appendage classes were identified. Four distinct speed ranges are identified for this: slow speeds (Fn = 0.10 to 0.20), operational speeds (Fn = 0.20 to 0.30), medium range speeds (Fn = 0.30 to 0.40) and sprint speeds (Fn = 0.40 to 0.45).

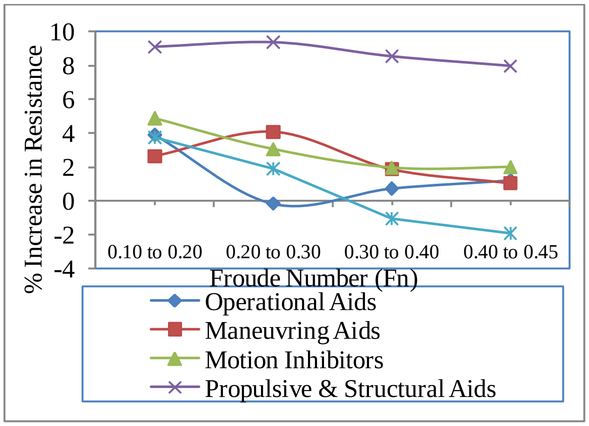

Figure 8: % Increase in resistance by appendage classes

The mean percentage variation in resistance in these speed zones were calculated for these appendage categories. The resistance contributions are summarised in Figure 8. The propulsive and structural appendages contribute maximum to the overall appendage drag. ESDs are found to reduce resistance at higher speeds.

5.Appendage Efficiency Index

While designing appendages for a ship's hull form, the designer would like to rate his design of appendages. The quality of an appendage should be benchmarked by weighing its operational effectiveness against the negative impact it has on the bare hull hydrodynamics of the ship. A universal standard for reviewing the effectiveness of an appendage will serve as a handy tool for the designer. In an attempt to compare and improve the performance of an appendage, the authors would like to propose such a system in this section as a starting point. To begin with, an Appendage Effectiveness Index (AEI) is put forward which represents the sum of Functional Effectiveness and Inhibitive Capacity of the appendage.

Appendage Effectiveness Index

=Functional Effectiveness ± Inhibitive Capacity

Functional Effectiveness will reflect the capability of the appendage to perform its intended function. Inhibitive Capacity will cover all the negative/positive impacts that the appendage will have on the hydrodynamics of the ship without this appendage.

For example, let us consider a rudder. Functional Effectiveness for a rudder will be a function of the control forces generated/degree of turn, turn rate, roll stabilizing effect, etc. Inhibitive Capacity for the rudder will encompass the additional drag, cavitation, induced vibrations and any adverse impact on propulsive efficiency among others. Each of these characteristics should be rated on a scale that varies from 0.0 to 1.0. Such a scale is to be arrived at after considering all available data on the performance of such an appendage. The minimum point on the scale should be for the worst performance and the maximum for the best known performance at present. This offers flexibility in allowing for future improvements in appendage design. This means that an appendage that is rated as 'good' today may not be good enough tomorrow when the benchmarks have improved.

Let us consider the example of a stern wedge fitted to a planing craft which is used as a survey boat. [9]

Purpose of fitment : Reduction of trim and heave for proper immersion of sensors housed on hull bottom.
Speed : Maximum Fn = 1.94
Operational Fn = 0.65

To meet the above requirement, hydrodynamic model tests were planned on a scaled down model. Stern wedges were designed and manufactured at model scale. Model tests were conducted with the stern wedge fitted to the model and the resistance, heave and trim were measured. The performance of the optimised wedge (wedge angle = 4 deg, chord length = 2 % of L_{BP}) is presented in Table 1.

Fn	$P_{E\_wedge}/P_{E\_bare\ hull}$	$H_{\_wedge}/H_{\_bare\ hull}$	$T_{\_wedge}/T_{\_bare\ hull}$
0.12	1.19	0.25	0.50
0.24	1.11	0.98	0.50
0.36	1.12	0.91	0.47
0.49	1.02	1.04	0.72
0.65	1.01	0.26	0.80
0.79	0.97	1.74	0.72
0.96	0.95	1.17	0.70
1.18	0.96	1.13	0.72
1.34	0.94	1.13	0.72
1.53	0.94	1.14	0.72
1.70	0.93	1.13	0.70
1.79	0.93	1.11	0.68
1.94	0.94	1.16	0.66

Table 1: Performance of stern wedge on planing boat

It may be seen that the wedge effectively reduces the running trim of the model. The upwards heave motion is also substantially reduced around the operational speed (Fn = 0.65). To compliment, the powering performance of the craft is also greatly reduced at Froude numbers greater than 0.65. [9]

Functional Effectiveness (+1.0):

1. Reduces trim and heave as required around 10 knots. (+1.0)
2. The increase in heave beyond 10 knots is irrelevant from operational perspective. (NA)

Inhibitive Capacity (-0.2):

1. The powering requirement around 10 knots is increased by 19% to 1% from 2 to 10 knots. This powering increment is comparable to data from available literature. Nevertheless, there are few optimised cases where the powering is increased by only 2% to 1%. Hence a rating of (-0.5) is given for this performance.
2. The powering is improved above 10 knots by 3 % to 7%. (+ 0.3)

Appendage Effectiveness Index = (+1.0) + (-0.2) = 0.8

On a scale of 0.0 to 1.0, an AEI rating of 0.8 seem to reflect very good design and performance of the appendage. The ratings used in this example are just for demonstration and can be standardised only with a performance database of similar devices.

6.Conclusion

The criticality of appendages in powering performance of ships was emphasized in this paper. Ship hull appendages were hydrodynamically classified into six categories. The resistance contributions of each of these categories of appendages were assessed through examples. Key points in design and evaluation of appendages were touched upon. The huge appendage drag on a warship was highlighted through a comparison with other ships. Sonar dome positioning was discussed for minimum added resistance.

The process of evaluating and redesigning appendages on a FDHFNA was demonstrated through a case study. Through the case study, the minimum appendages present on a warship, CFD studies for initial configurations, their evaluation and realignment through flow visualization studies and overall effect on ship resistance are brought out. The resistance contribution of each appendage was extracted. The application of Energy Saving Devices for reducing the powering requirement of the ship was also illustrated in this study. Overall, the resistance contributions of the different categories of appendages for the warship in picture were outlined.

An Appendage Effectiveness Index is proposed for rating and reviewing the quality of any appendage. At this stage, due to lack of a global database it is not possible to estimate AEIs for all appendages. However, an example is provided just to give a feel of the AEI estimation which the authors have in mind. Such a simple and flexible system would allow for comparing any appendage and thus improving its performance periodically.

7.Acknowledgement

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