Silverstream® System – Air Lubrication Performance Verification and Design Development

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Abstract

In this paper Silverstream Technologies present their experience of developing air lubrication technology and proving the effectiveness of their system through the use of tank testing, full scale sea trials and long term performance monitoring. The challenges of demonstrating in- service performance and the techniques used to account for weather and sea state effects are outlined, as are the developments in the design of the system to further increase its simplicity. The result of these efforts has led to proven net savings in excess of 4%, commercial contracts and projected savings of 8% percent across vessel types.

1. Introduction

Air lubrication has long been thought of as a viable method for reducing the frictional resistance of waterborne vessels. Many methods have been proposed and tested over the last decades, but no single method of achieving the desired net energy reduction has been fully adopted by the industry. Silverstream Technologies air lubrication system, the Silverstream® System was created from the experience gained through trialling differing designs, with varying degrees of success. This process of designing and testing in full scale began around a decade ago and has culminated in a constrained set of parameters that are used to achieve the efficient production of micro-bubbles beneath the ships hull.

The first installation of the Silverstream® System, that was retrofitted on the 40,000dwt chemical tanker M/T AMALIENBORG, was followed by ballast and laden sea trials. This demonstrated that the air lubrication system delivered overall net savings of 4.3% and 3.8% respectively. This initial installation was sponsored by Shell and the savings were independently verified by LR and HSVA. To go a step further, it was decided that the energy savings in normal operational conditions should be investigated. Over a period of 11 months of operation, performance data was collected and analysed to demonstrate actual energy savings, this showed savings in excess of 4% for unfavourable fully loaded deep draught conditions, the details of this analysis will be outlined in this paper.

The close cooperation of Dannebrog Rederi, the ship owner of this installation, has allowed Silverstream Technologies to monitor the vessel over the past two years of operation, answering many of the questions that are commonly raised with this technology. These include the effect of waves on performance, marine growth on the hull and air ingestion into the propeller, details of which will be outlined in this paper.

In addition to performance of the system, continued efforts have been made to improve the practicality and usability of the system reducing its impact on the crew and the vessel, making it more cost effective and easier to install. These developments include an updated control and monitoring that allows the system to self-adjust without crew intervention. The drag of the cavities when the system is switched OFF has also been reduced by over 50% through design optimisation and the results if this will be outlined in this paper.

2.0 In Service Performance Monitoring

The air lubrication technology has the main advantage that it can be switched ON and OFF at any time so that the resistance reduction effect can be immediately measured. A performance monitoring system has been installed on the vessel which collects all the required parameters for the reliable evaluation of performance and efficiency gain. High frequency data and 5-minute average data have been collected, these are primarily main engine RPM, speed through water and GPS, shaft power (torque), compressor power consumed, fuel consumption through mass flow meters and other weather parameters from the hindcast model.
An example of the effect of the Silverstream® System on the shaft power reduction and speed increase can be seen below in the 5-minute output data.

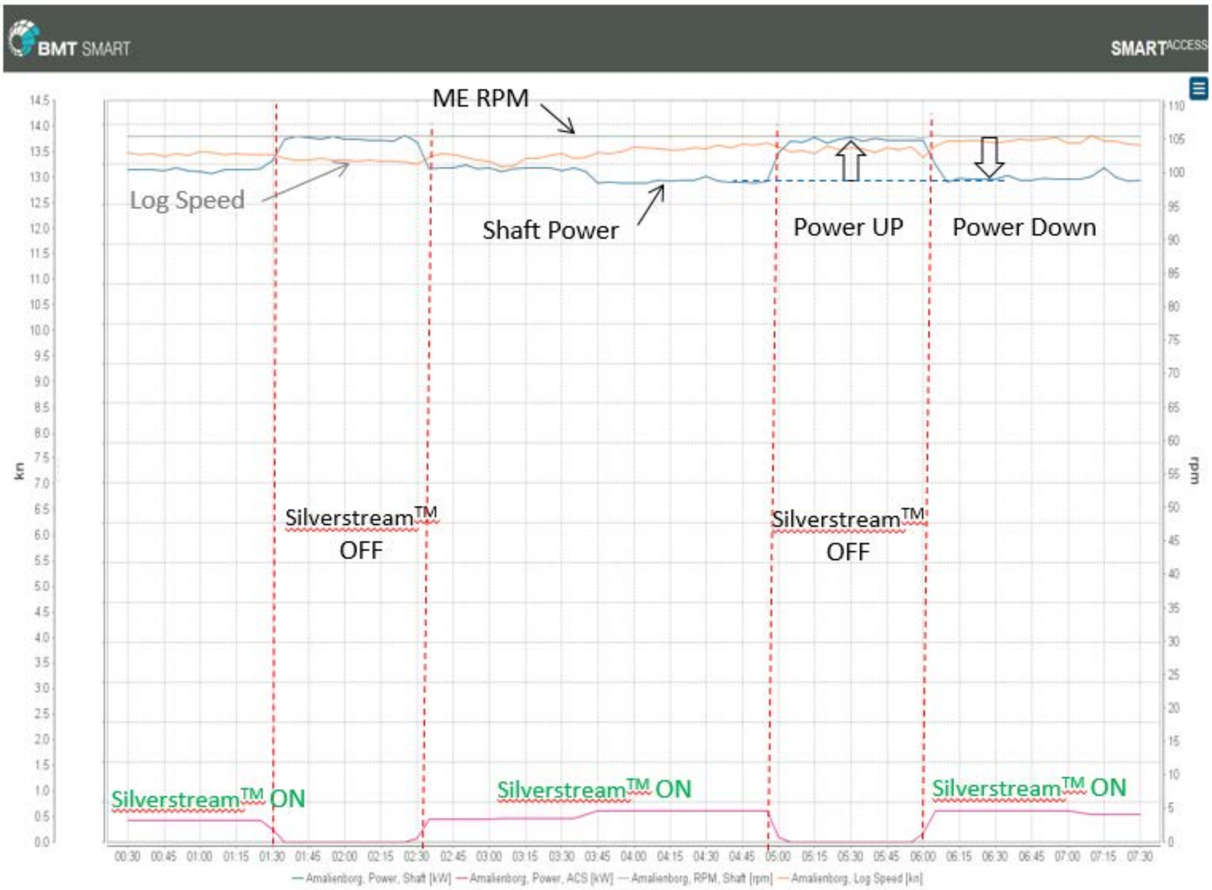

Figure 1 - Example Air Lubrication Effect from Monitoring System

2.1 Data Set

Given the complexity of analysing the in service performance of the vessel, which is affected by many variables most of which can become non-linear, it is necessary to organise and filter the data in a logical and accepted method. Guidance has been obtained from the draft ISO standard 19030, 'Measurement of Changes in Hull and Propeller Performance'. The performance data was filtered to include only moderate environmental conditions, it is Silverstream Technologies opinion that accurately monitoring and determining the performance in heavy seas introduces uncertainties in the results due to the non-linearity of ocean sea states and vessel response. This methodology is also reflected in the draft ISO standard 19030. The following criteria was used for the data filtering:

- Significant Wave Height < 2.5m (Sea State 4) – This is in line with the recommendations in ISO 15016 sea trials standard and reduces the influence of added resistance due to waves.
- True Wind Speed < 7.9 m/s (BF 4) – This is in line with the recommendations of the draft ISO 19030.
- Water depth > 60m – Water depth was limited to ensure shallow water effects were not included and in accordance with the draft ISO 19030. This also serves to increase the accuracy of hindcast data used to determine the wave height.
- Rudder Angle -1< Angle < 2 degrees – This is used to minimise the effect of added resistance due to rudder angle. As propeller rotation causes a small turning moment on the vessel, there is always a small positive rudder angle. The limitations, therefore, allowed for this constant small rudder angle.
- Rate of Turn < +/- 0.01 degrees/second – Data was filtered to remove the effects of manoeuvring, performance monitoring has shown that this has a significant effect on vessel speed and shaft power.
- RPM > 90 – Only of interest is vessel data whilst underway. Anytime the vessel is below 90 RPM indicates a transient phase (i.e. slowing down or speeding up) this should therefore be removed.
- Log Speed > 10 knots – Speeds below 10 knots were considered anomalies for RPM greater than 90 and removed.
- Shaft Power > 2500 kW (30% MCR) – The few data points where shaft power was less than 2500 kW for an RPM grater 90 are considered outliers and removed.
- Silverstream® System Power < 80 kW – To avoid 5 minute points which contain the transient period of system ON/OFF.

An 11 month data set was taken from the performance monitoring system for the period of March 2015 to January 2016. The filtered data was organised by loading condition, the predominant draught is laden between 10 to 11m, this accounts for 60% of the filtered data. Only 15% of the data was for ballast condition. As the vessel is predominantly trading in a laden condition, the proportion of ballast data in the observation period is insufficient for the analysis. The ballast data is also recorded over a limited range of RPM values, this causes unrealistic power curves to be plotted and results are considered to be inaccurate. For this reason, the analysis is limited to laden condition with average draught between 10 and 11m.

It has been found that increasing the draught range in the data set only serves to increase the inaccuracy of results as the separation of system ON and OFF data become blurred by the increase and/or decrease in vessel resistance due to the draught.

When sufficient ballast data is available, a similar analysis as outlined in this document to be undertaken as it has been shown that efficiency gain results are more favourable in the lower draught ballast condition. This is due to a larger proportion of the wetted surface area being lubricated and there is a lower power requirement for the compressors due to the lower back pressure.

2.2 Data Analysis

The initial data set included around 100,000, 5 minute average data points. After removing data through the filtering limitations described above, this data set was reduced to 13,800 data points that were considered in the performance analysis. This comprised around 8,400 'System ON' and 5,400 'System OFF' data points.

In order to determine the effect of the Silverstream® System the data was first divided into system ON and OFF. A scatter plot of the data points can be seen below in Figure 2.

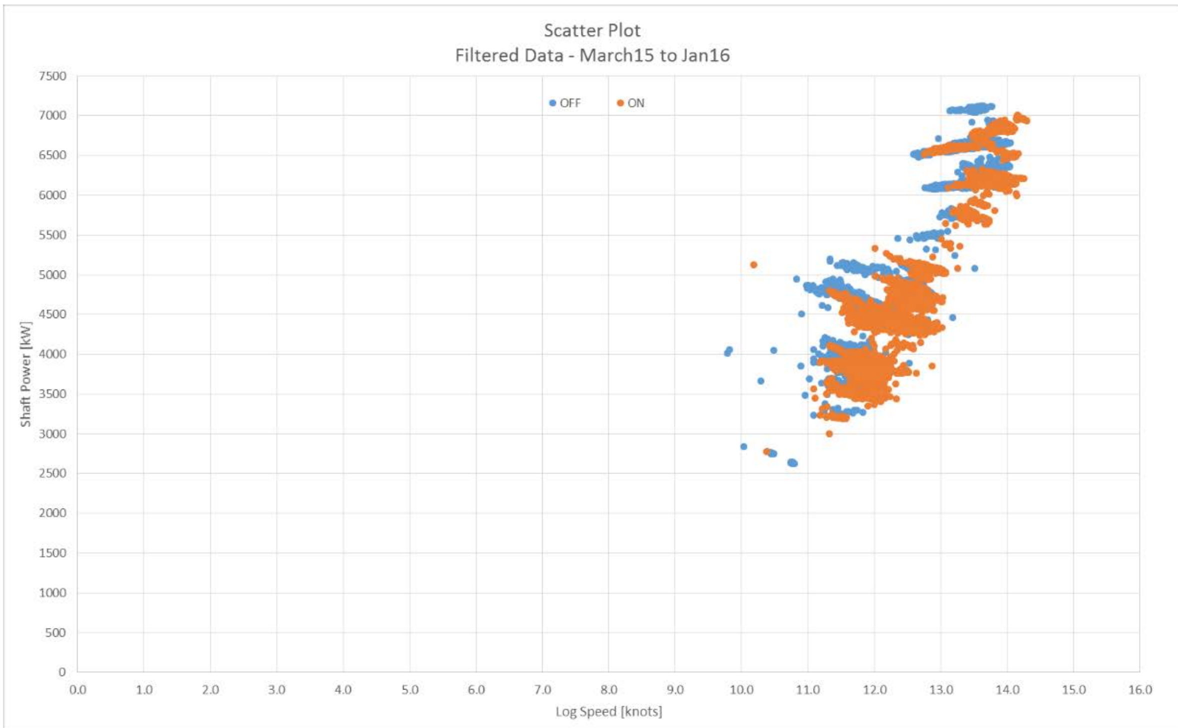

Figure 2 - Filtered Laden Data

It is not possible to accurately plot a speed-power trend line directly through a scatter plot, such as that seen in Figure 2, using automated graphing functions. The vessel does not spend an equal amount of time at each RPM and therefore there is not an equal number of system ON and OFF data points. The fitting of the power curve would be biased towards those speeds were most of the data points lie, the result of this is inaccurate fitting of the trend line.

For this reason, the system ON and OFF data is arranged in terms of shaft RPM and the average speed and power at each RPM is taken. With sufficient data, this forms a scatter plot of data points that can be used to estimate the power curve with equal weighting given to all RPMs (speed and power). The result of this ‘RPM averaged data’ is shown in Figure 3.

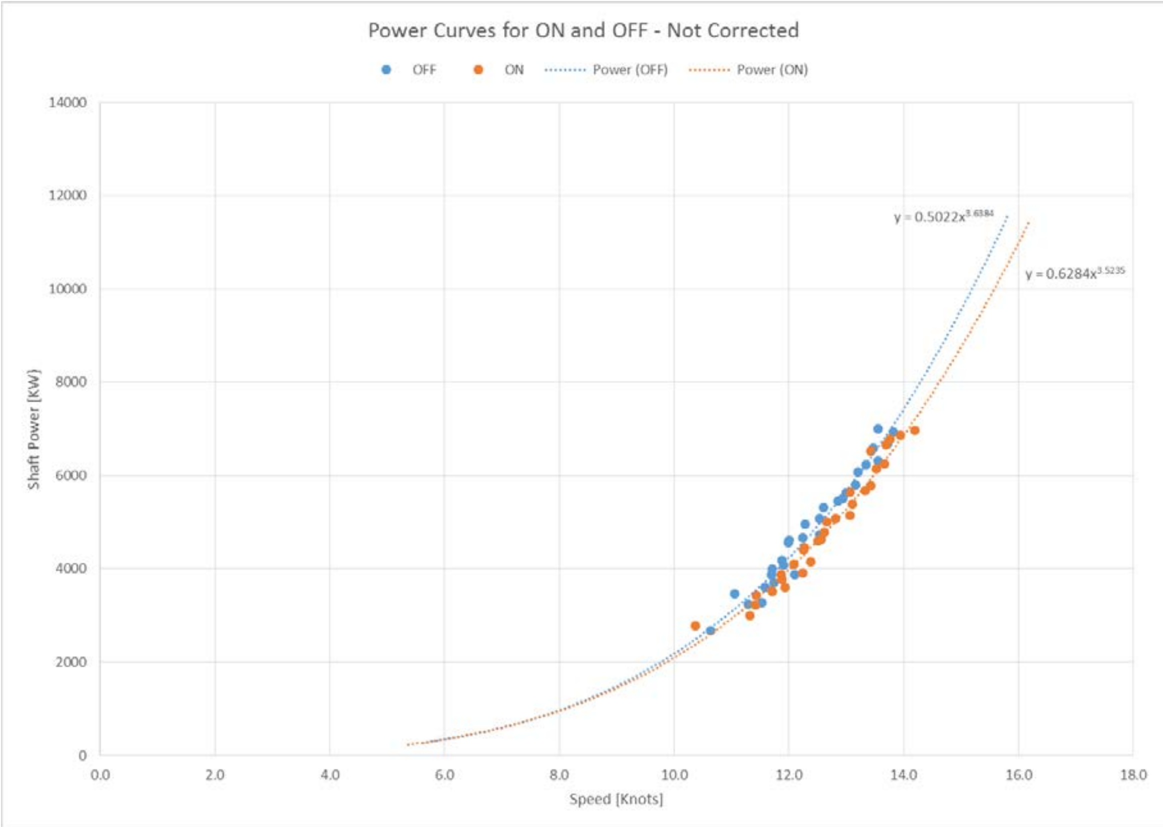

Figure 3 – Average Shaft Power for given RPM against Speed

The trend line is plotted using the regression function that produces a line with the formula $y = ax^b$. This is considered appropriate for the purpose of comparison of data, however the shape of a ships speed-power curve will likely be different.

Using the formula for the trend line for system ON and OFF data, the gross savings due to the air lubrication have been presented over the range of operating speeds in Table 1 below. It must be noted that the below values have not been corrected for compressor power or drag of the air release units and these savings represent the pure effect of the air on the hull resistance.

Log Speed knots	Shaft Power – OFF kW	Shaft Power – ON kW	Gross Saving kW	Gross Saving %
11	3089	2935	155	5.0%
11.5	3632	3432	199	5.5%
12	4240	3988	252	5.9%
12.5	4919	4605	314	6.4%
13	5673	5287	386	6.8%
13.5	6509	6039	470	7.2%
14	7429	6865	565	7.6%

Table 1 - Gross Power Savings (not corrected)

The power curve trend lines for system ON and OFF, shown in Figure 3, must be corrected to account for the additional drag of the air release units when the system is turned OFF and the consumption of the Silverstream® System. The drag was estimated for the AMALIENBORG through CFD calculations to be 1.3% of shaft power in laden condition. Therefore, the system OFF curve is reduced by 1.3% to allow for the fact that part of the efficiency gain is the reduction of the drag. Drag of the air release units will be further discussed in Section 5.0. The system ON curve is also adjusted by combining the average power consumption of the compressors at each RPM and the shaft power value. The corresponding separation of the curves is the therefore the net efficiency gain attributable to the air lubrication effect. This is shown below in Figure 4.

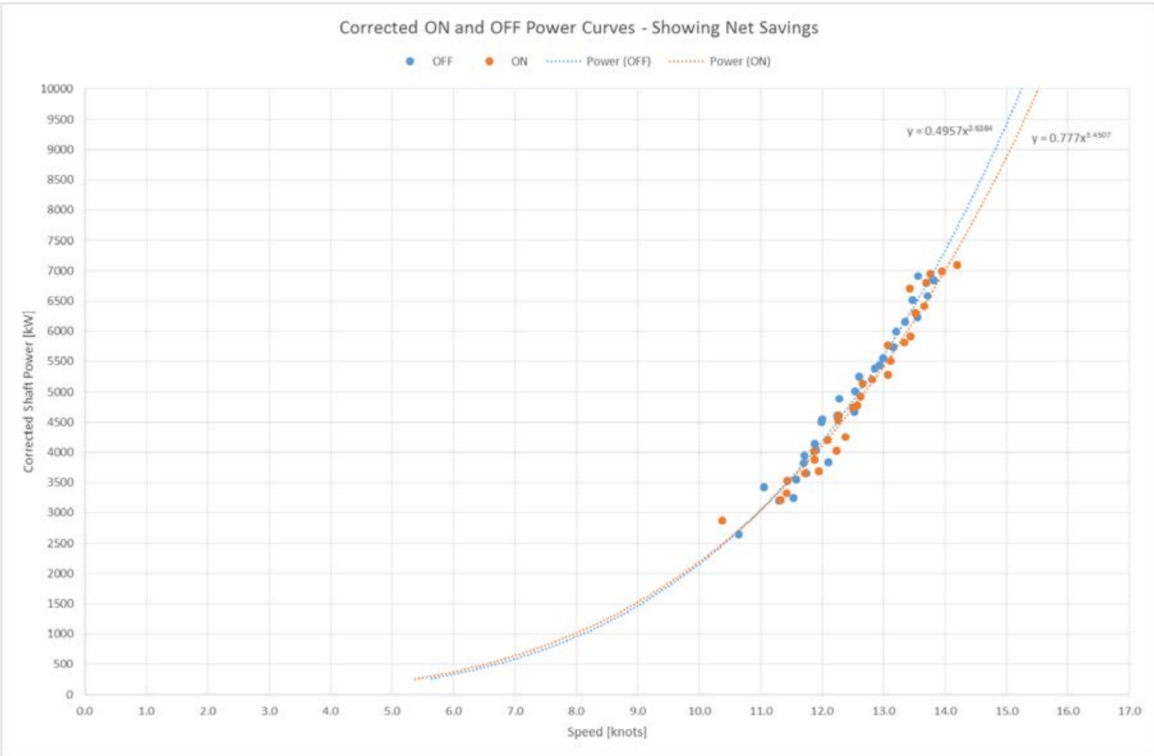

Figure 4 – Corrected Average Shaft Power for given RPM against Speed

Using the produced formula for the power curves of system ON and OFF data, the indicated net savings can be calculated over a range of vessel log speeds. These are presented for the operational range of the vessel in Table 2 and shows increasing savings with increasing speed.

Log Speed knots	Shaft Power - OFF kW	Shaft Power - ON kW	Net Power Saving kW	Net Saving %
11	3049	3048	2	0.1%
11.5	3585	3553	32	0.9%
12	4185	4115	70	1.7%
12.5	4855	4737	118	2.4%
13	5600	5424	176	3.2%
13.5	6424	6178	246	3.8%
14	7333	7004	329	4.5%

Table 2– Calculated Net Efficiency Results

3.0 Performance in Waves and the Path of Improvement (Skewed Ladder)

A question that is often asked about air lubrication is how effective the drag reduction remains when the vessel is operating is a seaway, pitching and rolling due to the waves. To demonstrate the effect, the following data shows how the air lubrication remains effective with increasing wave heights.

An example of a typical data set obtained over a three day period from 7th to 9th February 2015, is shown below in Figure 5. This was a period of constant main engine (ME) / Propeller RPM and with varying weather conditions. This was during a ballast voyage in the Indian Ocean where conditions were variable and significant wave heights ranged from 0.7 to 2.2 metres. These changing conditions combined with changes in heading of 80 degrees resulted in spreading of the ON/OFF results at constant RPM.

The shaft power is plotted against log speed for the system ON and OFF condition. As can be seen in the figure, we obtain a separation between the 'ON' and 'OFF' points and the data scatter exhibits a curved tail trend. Each point on the graph represents a 5 minute average value. The ballast speed-power curve of the vessel is also plotted to demonstrate that how the weather effects the performance.

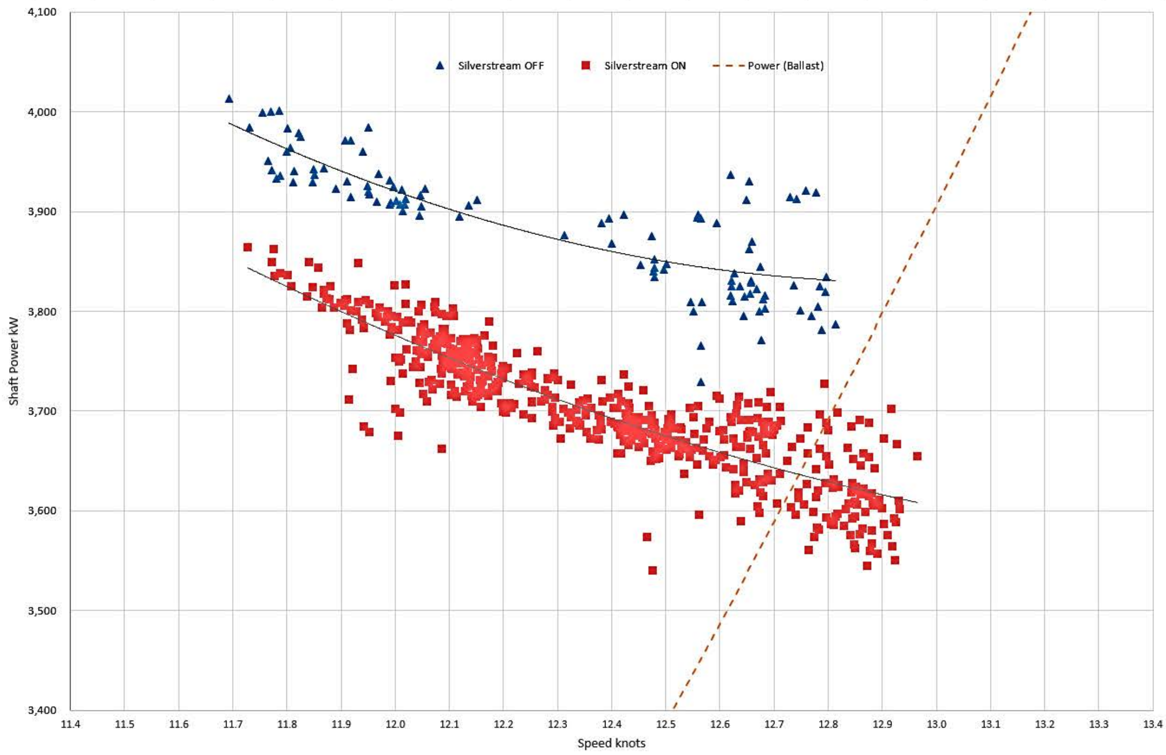

Figure 5 - Silverstream ON/OFF

We can see from the above plot that the vessel, with a fixed ME RPM setting, requires more power and moves slower through the water as it encounters heavier weather. Points to the right represent smaller wave heights with significant wave height (Hs)=0.75m and to the left, bigger waves of Hs=2.2m (maximum wave heights (Hmax) of 1.25m to 3.6m respectively). Angle of incidence of waves also has an effect, but provided the vessel maintains course, the changes are generally slower over time.

The system was turned OFF approximately twice per day for about one hour, in order to establish the baseline data for the prevailing conditions. In order to demonstrate how the performance changes when the system is operational, the data can be further divided into smaller time frames to capture similar headings and wave heights. The scatter plot below, Figure 6, shows multiple data sets for similar vessel headings on each of the three days.

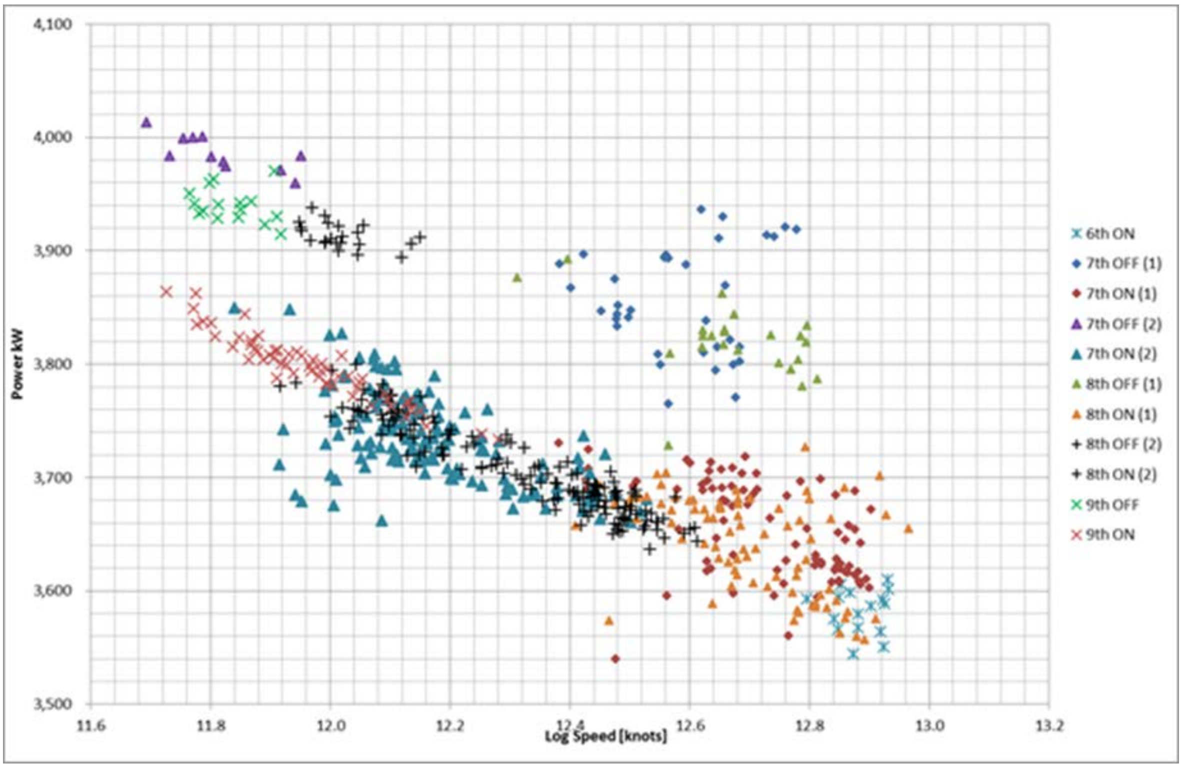

Figure 6 - Divided Data

It can be seen that the data falls into two groups, these relate to different headings, whilst the remaining scatter is due to the effect of added resistance due to waves. It is also shown that the results show a reduction of shaft power and a gain in speed when the system is activated.

Taking the average of each data group of ON/OFF periods shown in the above figure, and plotting these points onto the original data set, the shift of the trend line can be demonstrated based on this further analysis of the data.

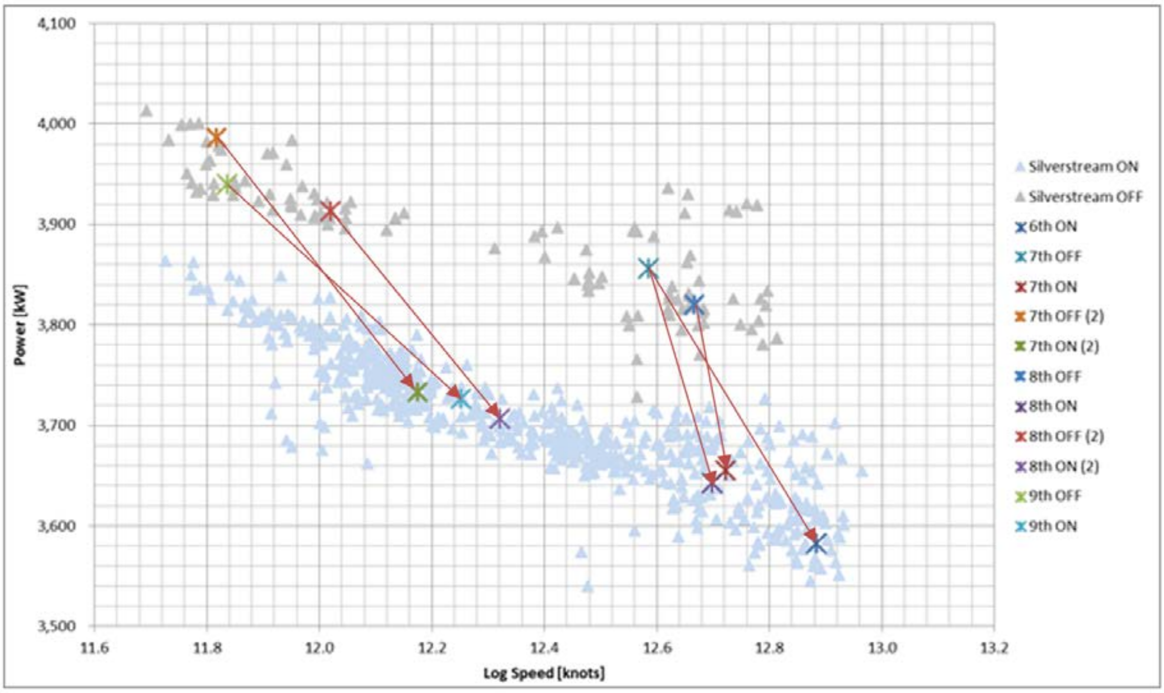

Figure 7 - 7th to 9th February Performance Shift due ON/OFF in Varying Weather Conditions

As can be observed from the change in all weather conditions that the power reduces and the speed increased. Although the changes do not always follow the same gradient, due to various factors, the underlying trend indicates that a function exists between the ON and conditions. The varying sea states giving rise to the indicated skewed ladder function, and demonstrating that the performance gain due to the Silverstream® System continues with increasing sea states.

4.0 Hull Coating and Propeller Condition

The most common questions around air lubrication technology surrounds the effect of the air bubble layer on the ships propeller and the hull surface. Before the first installation there were concerns that the micro-bubble layer created by the air release units could cause cavitation damage to the propeller or damage the paintwork, and even increase the hull fouling. It has since been demonstrated that these fears were onerous and the bubble carpet has no negative impact on the vessel.

Cavitation erosion is caused by the implosion of a vacuum bubble that collapses on the surface of the propeller due to rapid changes in pressure, this can lead to damage to the metal surface. The air bubbles introduced onto the hull bottom surface are pressurised bubbles of air and therefore cannot implode like a vacuum bubble to cause damage to the propeller. In addition, as the air layer is reducing the load on the propeller (by reducing the resistance) the chance of cavitation damage is also reduced as the operating point of the propeller moves away from the cavitation point.

To confirm this theory, measurements were taken during the sea trials and annual dive surveys have been carried out since the system installation. These have shown the propeller to be in good condition with no signs of damage or marine growth. It is therefore evident that the small quantity of air that may be ingested into the propeller poses no risk to cavitation damage. It is also evident that the condition of the propeller remains clean and there has been no requirement for propeller polishing, contrary to what might be expected two and half years after dry docking. The condition of the propeller on the second annual dive survey are shown below in Figure 8.

Figure 8 - Two Year Dive Survey - Propeller

The condition of the hull has also been closely monitored since the installation. Annual dive surveys confirm that the hull bottom was free of marine growth and the antifouling remains effective. In general, it can be said that the condition of the hull bottom appears in a good condition, and is considered better than what could be expected after two years of operation. Images of the hull condition from the second annual dive survey can be seen below in Figure 9.

Figure 9 - Two Year Dive Survey - Hull

The conclusions from this monitoring through regular dive surveys confirm that there are no adverse effects to the vessel from the air micro-bubble carpet. It is too early at this stage to conclude that the air bubbles are reducing the onset of hull and propeller fouling, although the evidence points to this significant secondary saving effect. Future dive surveys will provide further evidence for this added benefit from the Silverstream® System.

5.0 Air Release Unit Drag Reduction

Silverstream Technologies have invested significant effort in improving the simplicity and usability of its system. Besides improving the layout of the system to reduce the space requirements and advances in automation and control, significant reduction in the drag of the air release units have been made. They were modified to reduce the drag created in the event that the system is turned OFF. This was achieved by testing new patented configurations of the air release units.

A cavitation tunnel was used to simulate in full scale the conditions experienced beneath the ship hull. The resistance is measured directly in the cavitation tunnel, the air release unit is in full scale and the water is at real speeds. First, the resistance of the whole model of the plate with the air release units closed is measured and then the resistance of the whole plate with air release units 'open' is measured. Each air release unit was also tested to ensure the lubricating bubble layer was produced effectively.

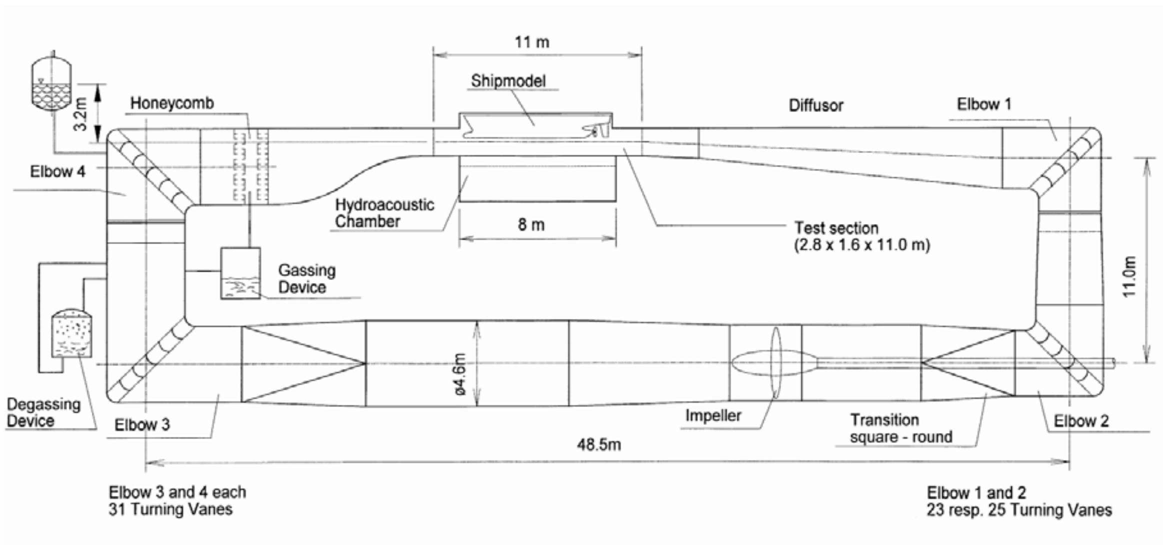

Figure 10 – HSVA HYKAT Layout

The force is measured on a plate around 8m long, this includes the air release unit along with an area of plate downstream. Therefore, the resistance measurement will also capture the turbulent flow created downstream of the air release unit. The graph below shows the measured resistance of one air release unit when the system is turned OFF (no air supply) the previous 2015 design, along with the current 2016 design of air release unit.

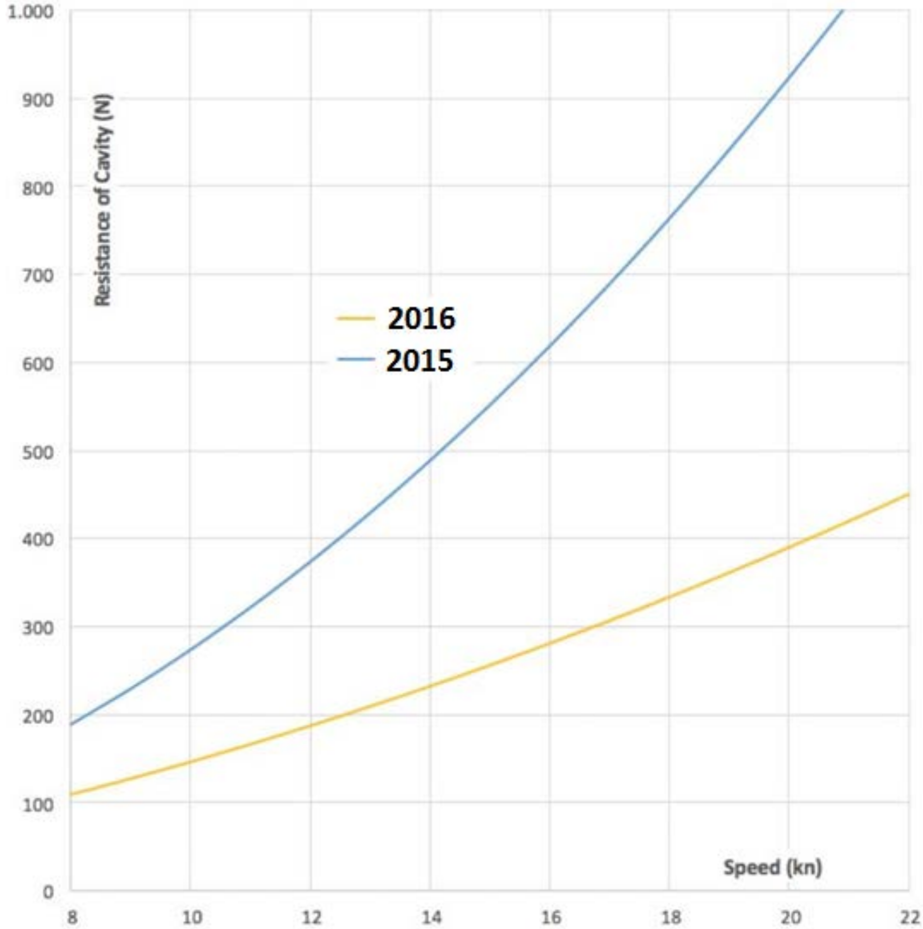

Figure 11 - Drag Comparison Based on HSVA Data

Based on the measured drag of the air release unit, the overall effect on a typical cruise vessel can be calculated for both the 2015 and 2016 design. The vessel resistance is calculated using an estimated propulsion efficiency and comparing the increase in resistance of a complete Silverstream® System installed in the hull bottom, without the air compressors activated.

Speed	Vessel Resistance	ARU 2015 Resistance (14)	ARU 2016 Resistance (14)	**ARU 2015 Resistance (14)**	**ARU 2016 Resistance (14)**
[kn]	[N]	[N]	[N]	**% of Total**	**% of Total**
15	867013	7725	3584	**0.89%**	**0.41%**
18	1248345	10689	4667	**0.86%**	**0.37%**
20	1541096	12928	5456	**0.84%**	**0.35%**

Table 3 – Air Release Unit Drag % of Ship Resistance

The above calculation shows clearly the 2016 insert design delivers over 50% reduction in drag compared with the 2015 design and has a calculated resistance of 0.35% at 20 knots. The previous insert resistance had a calculated increase of 0.84% at 20 knots for a typical cruise vessel. Estimates have been made for other vessel types such as LNGCs which confirm negligible resistance increase due to the air release unit design.

6.0 Conclusions

6.1 Conclusions from In-Service Performance Monitoring

- A method for calculating the long term efficiency gain has been developed and is considered sufficiently robust.
- The analysis indicates increased efficiency savings with increasing speed that is consistent with previous tank testing and sea trials findings.
- At current vessel operating speeds of 14 knots, equivalent to 70% MCR, gross savings of 7.6% and net savings of 4.5% have been demonstrated.
- The Silverstream System continues to work effectively in service and provides a long term benefit in terms of energy and consequential fuel saving.
- It is reasonable to conclude from the findings and tank tests that a vessel with higher operating speeds greater than 17 knots and with a larger lubricated flat bottom area can expect savings of 6% to 8%.

6.2 Conclusions of Hull and Propeller Monitoring

- The air bubble layer poses no risk to cavitation damage to the propeller.
- The air bubble layer has not eroded or damaged the antifouling coat of the hull.
- The air bubble layer has not affected hull fouling and evidence suggests that marine growth may be inhibited on the flat bottom and the propeller.

6.3 Conclusions of the Drag Reduction

- Overall relative drag effect of the air release units reduces with speed.
- The drag has been reduced by over 50% compared to previous designs whilst maintaining the lubrication effect.
- Estimated drag of the air release units for an LNGC or typical cruise vessel is well below 0.5%.

7.0 References

Lloyd's Register, Technical Investigation Department, '*Silverstream Technologies' Deep Load Condition Trial Analysis, December 2014'*.

Silverstream Technologies, '*Data and Discussion on the Performance of the Silverstream® System in Waves*'.

Silverstream Technologies, '*M/V AMALIENBORG, Long Term Performance Monitoring of the Silverstream® System*'

Draft ISO standard 19030, '*Measurement of Changes in Hull and Propeller Performance*'.
ISO 15016, '*Ships and marine technology – Guidelines for the assessment of speed and power performance by analysis of speed trial data*'.

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