CONCEPTUAL IDEAS ON A DOUBLE SURFACE SAIL INFLATED BY DYNAMIC PRESSURE

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This paper presents conceptual ideas on an unconventional sailing system. It is designed in principle and compared in terms of performance with two established sailing systems.

The concept is a double surface sail, which is to be inflated by the dynamic pressure at the leading edge of the profile. The fundamental principle is the same as used by paragliders and kites, where openings at the leading edge of the wing allow the air to “fill” the profile to give it a beneficial aerodynamic shape.

For the analysis of the structural mechanics of the sail system qualitative model tests in a wind tunnel are conducted. A profile segment is exposed to different angles of attack and the trim mechanism of mast rotation is varied. The resulting profile shapes and the profiles of the comparative sail types are then analysed to determine their characteristics by conducting 2D flow simulations. Also the effects of mast rotation to change the profile characteristics of camber and thickness are reviewed.

The double surface sail showed a good-natured behaviour at a wide range of angles of attack and a competitive performance potential compared to conventional sail sections and a wing sail section.

NOMENCLATURE

α	Angle of attack (effective)	*(°)*
α_{nom}	Angle of attack (nominal)	*(°)*
β	Mast rotation angle	*(°)*
c	Chord length	*(m)*
C_D	Drag coefficient	*(-)*
C_L	Lift coefficient	*(-)*
Re	Reynolds number	*(-)*
v	Wind velocity	$(^m/_s)$

2D	Two dimensional
3D	Three dimensional
AoA	Angle of attack
Bft.	Beaufort
CFD	Computational fluid dynamics
DSS	Double surface sail
FSI	Fluid structure interaction
NACA	National Advisory Committee for Aeronautics

1 INTRODUCTION

Current developments in competitive yachting show more and more wing sails being used as they become allowed by class rules. That is because they have a greater performance potential compared to single surface sails.

However, there are some disadvantages associated with the better performance; the handling is much more complicated and difficult. In most cases the sail cannot be hoisted nor pulled down on board by the crew. Reducing sail area is also not possible or complicated. Modern wing sails are usually split in two or three chord-wise segments to create an adjustable asymmetric profile shape. The control mechanism of these flaps is complex and therefore maintenance intensive if breakdowns are to be avoided. It also raises the weight of the system. The thin covering of the wings is not very robust against physical impacts.

In the past there have been some attempts to build a good aerodynamic profile from flexible materials, but so far none of them have been utilised by the sailing community. They were either too heavy or too complicated to use. Several concepts suggest using vertically arranged inflated battens between two sail surfaces [1] [2]. Other designs use inflated horizontal battens where the shape is controlled by varying the batten pressure.

In a literature review on different kinds of double surface sails (DSS), only two designs utilise dynamic pressure to fill the sail with air [3] [4]. One is composed of two sail surfaces, which are attached to the port and starboard side of the mast. To set the sail to one tack the mast rotates a little, that way the leading edge moves towards the windward side and a special structure at the leech goes over, so that the high pressure side is shortened and the suction side is lengthened. This flap mechanism seems to be complex to realise and complicated to use. The other concept is more similar to the one presented here. The sail wraps around a rotatable cylindrical device, which is positioned behind the mast where the standard sail is normally hoisted. The leading edge is therefore located in the mast wake, which has a negative influence on the performance potential.

Besides some patent specification and general ideas, little supporting academic work or scientific studies in relation to maritime applications were found. In Marchaj's 'Aero-Hydrodynamics Of Sailing' [5] so called lined sails are introduced where foam material layers are inserted between two cloth layers. However, wind tunnel tests showed less potential of these half rigid sails compared to single surface sails.

Research on different types of glider wings by Princeton University showed promising results for the performance potential of the semi rigid double surface wings [6]. The results are compared to this work later in the paper. The common ban of DSS and wing sails in most class rules for professional yachting events in the past might be a reason for the very limited research and development activities.

In aviation the idea of wings made from flexible material has developed well, as can be seen by modern parachutes and paragliders. Some kites also work with the same principles.

The aim is therefore to develop a concept of a flexible DSS for sailing boats. This requires solutions to let the DSS be formed asymmetrically to both sides to enable sailing on both tacks.

A concept has been developed, which tries to address some of the shortcomings of other systems; weight, complexity and usability. The complete device has the purpose to create a stable and favourable aerodynamic lift-generating airfoil to provide better performance than conventional single surface sails. At the same time the device should be light weight and storable to make it more practical than rigid wing sails. The working principles, qualitative wind tunnel test results of a two dimensional section and a comparison to other sail types sections based on 2D flow simulations are presented in this paper.

2 WORKING PRINCIPLES

The beneficial aerodynamic profile is created in nearly the same way as done in paragliders and foil-kites, with the difference that the system is able to change the side of the camber. The double surface cloth or laminated sail wraps around the mast and is attached to the front of the mast. At the trailing edge the surfaces run together to form the leech. The mast can be rotated to regulate the camber and profile thickness of the sail. Mast and sail surfaces have superposed openings on both sides of the mast. The sail openings can be controlled by a special valve system.

Fig. 1 shows the profile of the sail viewed from the top. In case of wind coming from the port side the mast is rotated clockwise. By that the openings on the port side of the mast and sail come towards the leading edge close to the forward stagnation point. The increased pressure in this region passes through the opening in mast and sail into the DSS. In this position the opposite openings on the suction side of the sail are closed by the value system.

A special structure inside the DSS is conceived to prevent the two surfaces to separate too much from each other and form bloated shapes. This can be achieved by strings or membranes between the two surfaces. Membranes have the advantage of preventing span-wise flow inside the sail, but non-shear resistant material should be used to permit chord-wise movement between the two sail surfaces. Utilising strings allows this movement.

Due to the increased pressure between the two sail surfaces and their spacial separation a comparatively stable and stiff structure is generated. Since this sail system needs no rigid components apart from the mast, it is possible to store and reef it. The only extra effort in terms of trimming the sail is controlling the mast rotation and the valve system for the sail openings. It is conceivable that the valves can be opened and closed automatically when tacking.

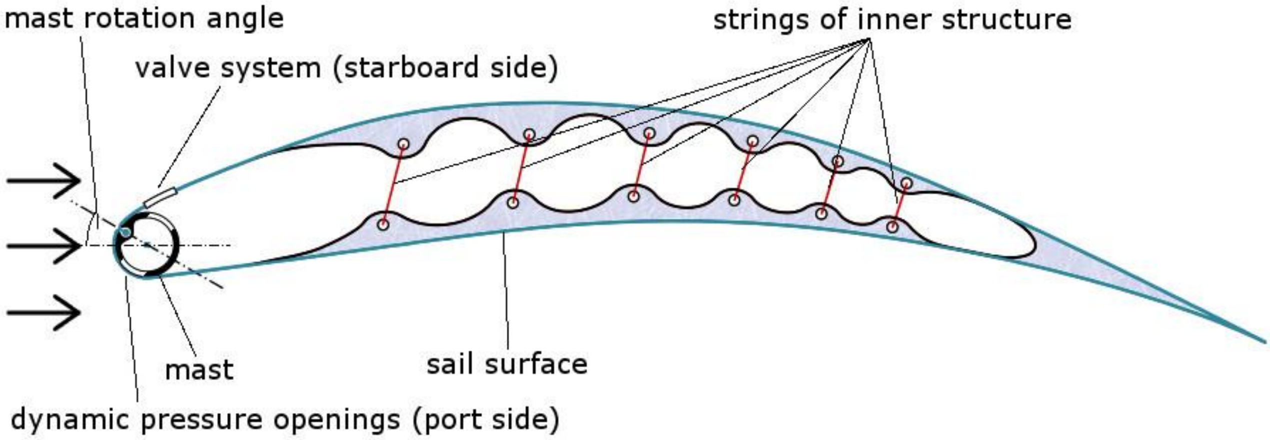

Figure 1: Section structure of the DSS concept

Through the mast rotation it is possible to adjust the thickness of the profile.

3 ANALYSIS PROCEDURE

A common way to analyse a sail system is to conduct model tests and measure the forces. When using computational fluid dynamics (CFD) to assess a sail, which is made from some kind of flexible material like cloth, a prediction of the distortion due the aerodynamic forces is needed to obtain realistic results. Nowadays a complete simulation of the fluid structure interaction (FSI) is typical for commonly used sail systems.

For this new conceptual design a combination of wind tunnel tests and CFD simulations is chosen to assess the concept in a physical hands-on way. Qualitative model tests are conducted to proof the concept and obtain the sail shape. CFD simulations for the resulting sail shape are performed afterwards. In this study the analysis of the DDS system is conducted for a 2D section. A 3D investigation is regarded as too extensive for this conceptual work as many other factors would influence the performance comparison of the different sail types. It is therefore seen as most interesting and feasible to look at the sectional behaviour compared to other sail systems for this initial investigation into the concept.

First a 2D section model is made and tested in a wind tunnel to assess the structural behaviour. Afterwards the achieved profile shapes are analysed by running a 2D flow simulation. Thereby only close-hauled courses are considered. To compare the predicted performance potential flow simulations of a rigid wing sail profile and a conventional single surface sail profile are also performed.

4 WIND TUNNEL TESTS FOR PROFILE SHAPE ANALYSIS

4.1 TESTING FACILITIES AND MODEL

The deployed wind tunnel is part of the testing facilities of the institute for dynamics of maritime systems at Technical University of Berlin. The test section has a cross section of $0.5m \times 0.3m$ and the maximal wind speed is $v=6m/s$.

The focus of this investigation is the behaviour of the profile section. A 3D assessment and comparison to other sail types is seen as unrealistic as part of this conceptual project due to the resulting model complexity and accuracy. A quasi-endless 2D model is used in the wind tunnel (Fig. 2). It is assumed that the gap at the top and the bottom of the model is small enough to prevent significant loss of pressure inside the DSS. To account for scaling effects the model is constructed of very thin and light sailcloth so that the fold ratio shows comparable stiffness to full-scale sailcloth [7]. For the mast an aluminium pipe is used. The chord length is about $c=340mm$ and the mast diameter is $20mm$. The model is fixed to synchronously rotatable disks in the floor and ceiling of the testing section. They can be adjusted to $\pm 40°$. The mast pivot passes through the tunnel ceiling and can be adjusted from the outside to any angle.

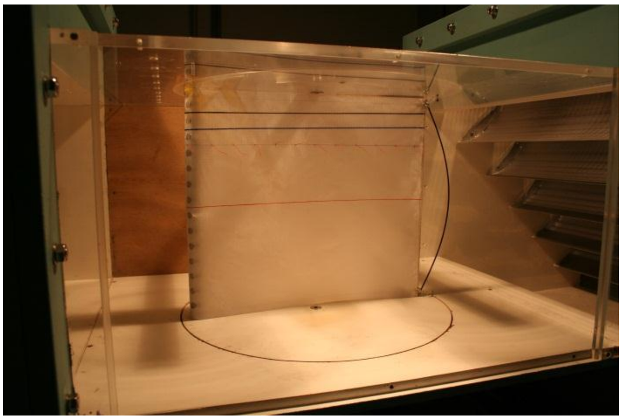

Figure 2: Model in test section

Additionally there are tell-tales along one circumference, so that separation effects can be detected.

4.2 TESTING PROCEDURE AND ANALYSIS

The wind speed is set to $v=3.25^{m}/_{s}$, which is equivalent to a Reynolds number of about $Re=0.8 \cdot 10^{5}$. At that speed the model behaves consistently and the stiffness is still adequate at large angles of attack (AoA). At higher speeds the gaps between the model and the tunnel ceiling and floor increase due to sail cloth stretch, so that the two dimensionality of the flow and the pressure inside the DDS would not be maintained.

The rotatable disks are set to nominal angles of attack of $3°$, $5°$, $7°$, $10°$, $15°$ and $25°$. The effective AoA is always about $2.5°$ lower since the trailing edge is not fully constrained against moving sideways. The test cases are labelled based on nominal AoA combined with the mast rotation (e.g.: $\alpha_{nom}=5°$, $\beta=30°$ → 05_30). The mast rotation is varied from $\beta=0°$ to $\beta=50°$ in increments of $10°$.

Through the transparent ceiling of the test section photos are taken from above the centre of rotation, so that the profile shapes in the different combinations of AoA and mast rotation can be observed (Fig. 3).

Altogether there are 36 tested combinations of AoA and mast rotation. For closer investigation six cases with different mast rotation angles at the same AoA and six modulations of AoA with fixed mast rotation are chosen. By that the influence of these two values can be assessed separately. The other combinations show trends, which

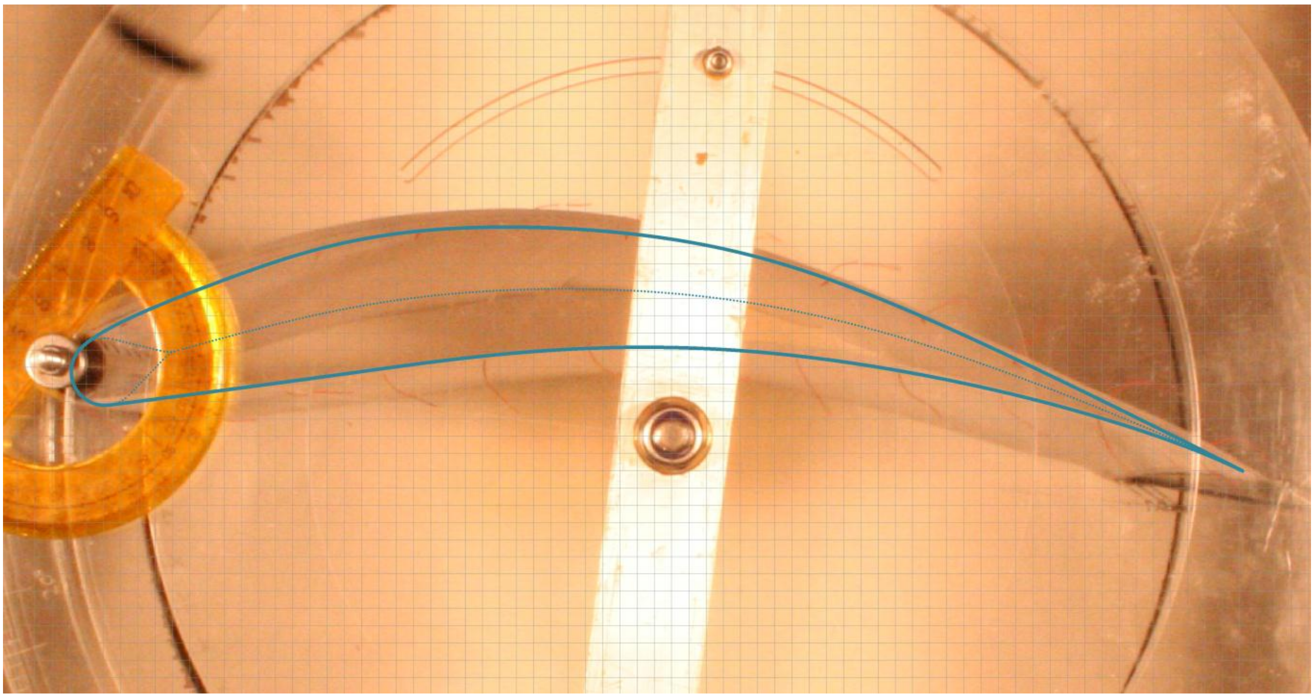

Figure 3: Profile section in wind tunnel with digitised shape, $\alpha_{nom}=7°$, mast rotation angle $\beta=30°$

can largely be explained by the two systematic variations.

The photos of all reviewed cases were digitised in a computer aided design (CAD) programme by manually tracing the section shape. As an orientation aid the tell-tales along the circumference were used. Fig. 3 shows the digitised section profile in the photo (case 07_30).

4.3 QUALITATIVE MODEL TEST RESULTS

The digitised shapes of the selected section profiles are shown in Fig. 4 and Fig. 5. In Fig. 4 one case ($\alpha_{nom}=15°$; $\beta=30°$) is shown where the windward surface shape is inverted. The pressure inside the DDS is higher than the pressure on the windward side so that this convex shape occurs. Presumably the openings in the sail at the leading edge are close to the stagnation point, which creates the high internal pressure. The same effect can be observed for the other five test cases at $\alpha_{nom}=15°$ and six further combinations (03_50, 05_50, 07_50, 07_40, 25_20, 25_10). These shapes are not considered in the analysis since they are not suitable for lifting devices with a high C_L/C_D ratio. This behaviour could possibly be avoided with an inner structure to limit spacial separation of the two surfaces, which was omitted due to the small scale model, or by reducing the size of the leading edge openings to lower the internal pressure.

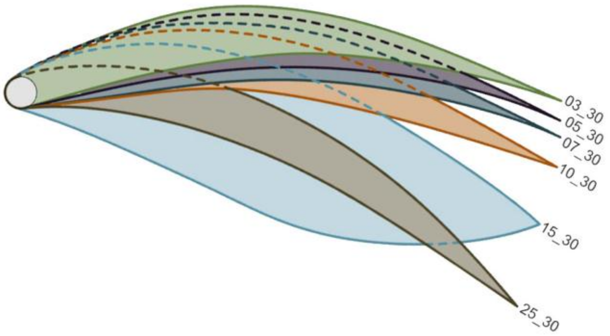

Figure 4: Variation of AoA with fixed mast rotation angle of $\beta=30°$

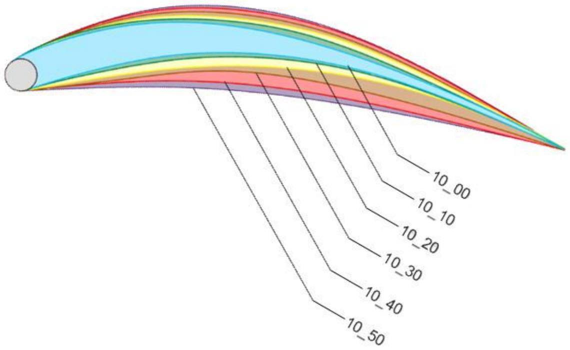

Figure 5: Variation of mast rotation angle with fixed AoA of $\alpha_{nom}=10°$

The twelve pairs of equidistantly spaced tell-tales show first signs of separation near the trailing edge of the suction side for AoAs greater than $\alpha_{nom}=10°$ and at every case with mast rotation angle of $\beta=50°$. This observation can be explained by the fact that the suction side is highly curved at these large mast rotation angles. At an AoA of $\alpha_{nom}=25°$ wide areas of separation are visible for all mast rotation angles.

By closing all dynamic pressure openings on both sides the sail section model showed a different shape being flatter immediately behind the mast. Noticeable was the back winding and a less stable behaviour for small AoAs.

5 AERODYNAMIC SIMULATIONS

By conducting 2D flow simulations the aerodynamic characteristics of the different sail sections are assessed. The focus is set on the potential performance, expressed by the lift (C_L) and drag (C_D) coefficient at the different AoAs. These coefficients are the dimensionless values of the lift and drag force affecting the aerodynamic body in a flow. They are normalised with the dynamic pressure and chord length [8], which is set to $c=1$ for all simulations presented here.

Furthermore a point of interest is the width of the AoA sector, in which good performance is achieved. This characteristic is beneficial to cope with apparent wind angle fluctuations.

For the aerodynamic simulation the software XFLR5[1] is used, which is in essence XFOIL extended by a GUI. It uses a 2D panel code with boundary layer condition for calculation of the profile circulation [8].

5.2 SIMULATION PROCEDURE

To compare the effectiveness of the DSS with established sails and wings, profile shapes of these types are analysed as well.

For every DSS shape at a tested AoA a sail shape is created. The most important factors influencing the drag of aerodynamic bodies are the thickness-to-length ratio, the position of the maximum thickness and the shape of the nose [5]. Considering this, the mean profile line of the corresponding DSS attached to a mast with the same dimension is chosen for the single surface sail (Fig. 6). Thereby camber is not changed and a good comparability is achieved. A mast pocket is constructed to emulate a possible application of a single surface sail on a dinghy.

For the wing sail section the NACA 0016 profile is chosen [9]. It has the same nose radius as the DSS and the cloth sail emulation since it was used as the reference profile for dimensioning the DDS. In order to obtain an asymmetric profile which can be utilised on both tacks, a flap is introduced at 50% of the chord length. To achieve the same camber as the DSS and sail emulation, the flap angle has to be $27.3°$. The fluid simulation showed excessive separation effects with this profile configuration. Also it seems not to be practical. Therefore the flap angle was reduced to $10°$. At this setting no more separation effects are recognised. Hence efficiency lost is reduced. The thickness-to-length ratio is slightly larger than the DSS, which has to be remembered when comparing the results; the NACA profile drag is overrated.

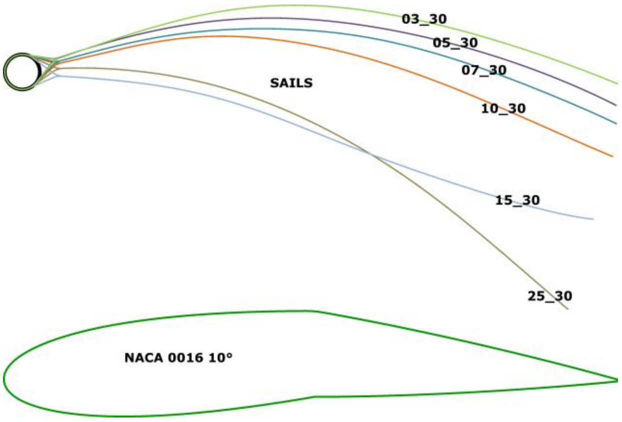

Figure 6: Profiles for comparison (top: sail emulations, bottom: wing sail profile)

In the flow simulation the effective angle of attack obtained from the photographs is used. Assuming an average wind speed of $v=6\,^{m}/_{s}$ $(\approx 3\text{-}4Bft.)$ and a chord length of $c=2m$ the Reynolds number is about $Re=0.8\cdot10^{6}$, which is used in the conducted simulation. These values are representative of high performance sailing dinghies like the moth class boats, on which prototyping such a sail system is conceivable and complies with the class rules.

The openings at the suction side are omitted to simplify the simulation. It is supposed that they do not interfere with the flow significantly, when the sail is filled with the stagnation point pressure. Furthermore the flow inside the sail is not considered. It has yet to be determined what the exact effect will be, but it is supposed that the dynamic pressure is different at the head and the foot of the sail and therefore a flow inside the DSS is possible to appear. To avoid that kind of undesired flow horizontal divisions would be possible, but they could reduce the ability of the structure to produce the observed shapes.

5.3 SIMULATION RESULTS

5.3.1 Analysis of variation of AoA

For the performance comparison exemplarily the five profiles with the same mast rotation of $\beta=30°$ and varied

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[1] Deperrois, A. ‘XFLR5 v6.05 beta’, 2011

AoA are taken. This way there are five data points each for the DSS and the sail emulation. Due to the immutable profile of the wing section, a finer resolution of AoAs is chosen (Fig. 7).

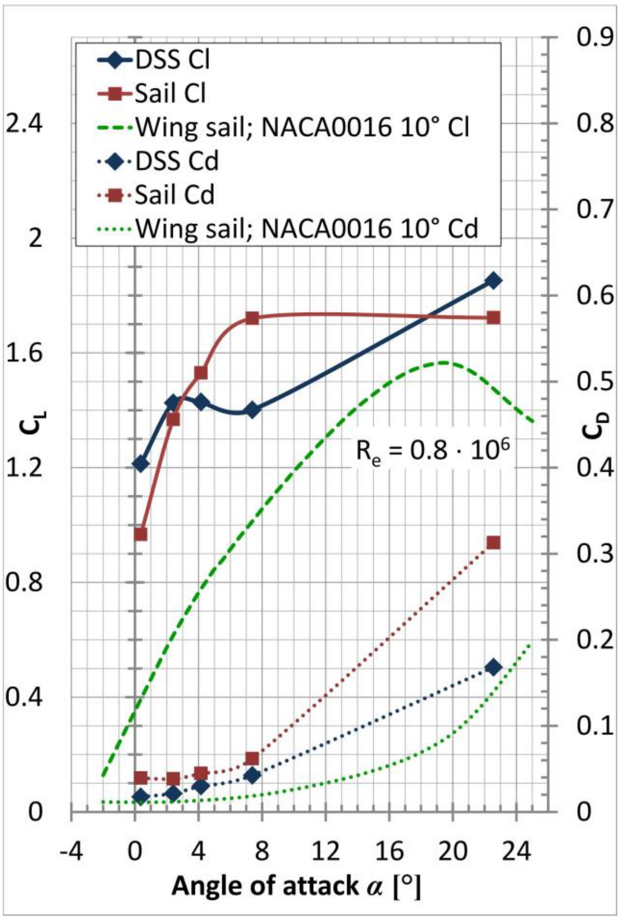

Figure 7: C_L and C_D comparison (2D sections)

The 2D fluid simulation indicates potential of the DDS compared to a standard single surface sail and a wing sail. It can be seen that the lift coefficient of the DSS decreases and drag rises noticeably between $\alpha=4.16°$ and $\alpha=7.39°$, which can be explained by the observed separation effects. As discussed later less mast rotation angle could reduce or eliminate this behaviour. The flapped NACA profile has the smoothest curves and reaches the maximal lift to drag ratio at the largest AoA, because it has less mean camber and consists of symmetrical segments. The low drag of the NACA profile over a large range of AoAs is due to the general characteristic of the 4-digit series to have a wide sector of attached flow [9]. The single surface sail has the highest drag coefficient because of the presence of the mast.

Generally aerodynamic profiles with a thickness are advantageous over cambered plates above a Reynolds number of $Re=0.15\cdot10^6$ [5], which would represent a wind speed of about *2* Beaufort for a conventional sailing dinghy.

Fig. 8 shows the lift to drag ratio of the three 2D profiles. However, it has to be remembered that the wing sail section is thicker than would typically be used and the flap position and angle is not necessarily set to an ideal value. The mast of an optimised single surface sail would be much thinner and may have an aerodynamic shape. Therefore the characteristics of both reference profiles are probably underrated.

But even by considering these arguments the DSS shows a high performance potential. A fluid simulation of a thinner wing sail profile (NACA 0010) with *10°* and *27°* flap angle produced a maximal C_L/C_D ratio of *70*, which is about the value the DSS achieves. An adjustment was also made for the single surface sail. The mast diameter was reduced by 40% for the case 10_30 ($\alpha_{nom}=10°$, $\beta=30°$) to approximate the rig proportions of an International Moth. The simulation shows a reduction in drag coefficient of about $C_D=0.005$. The resulting maximum C_L/C_D ratio of about *43* still remains below the maximum of *69* for the DSS. Consequently the difference between the DSS and the sail emulation is about 40%.

A study at the Princeton University on the aerodynamic characteristics of different glider wings showed comparable performance differences between a profile section with an elliptical nose and a single cloth surface, which resembles the sail emulation, and a profile section similar to the DSS. Wind tunnel tests were conducted at a Reynolds number of $Re=0.23\cdot10^6$ with 3D wing models with an aspect ratio of 8.5. The tests showed an approximately 45% lower C_L/C_D ratio for the single surface type [6].

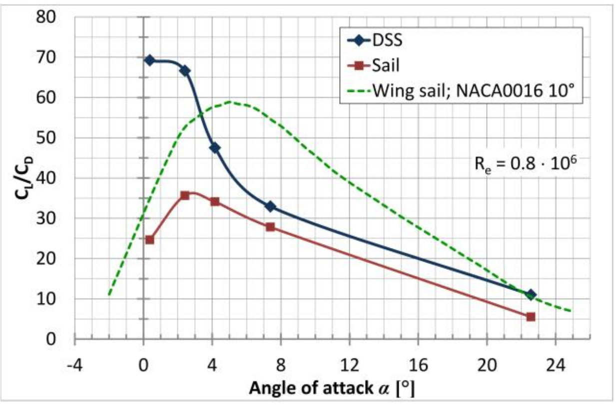

Figure 8: C_L/C_D ratio over AoA (2D sections)

Clearly visible in Fig. 8 is a narrow peak of maximal lift to drag ratio for the sail emulation. This characteristic is typical and one disadvantage of single cloth sails. The wing sail on the other hand shows the well-tempered behaviour followed by the DSS. The C_L/C_D ratio of the DSS remains nearly constant over a range of *3°* in AoA.

Not considered in the context of this project is the variation of the chord length (outhaul tension) to optimise the profile shape. Although it is an important trim parameter to change camber, the effect on the single surface sail and the DSS is expected to be similar so that the relative performance should remain comparable.

5.3.2 Analysis of the mast rotation angle

The DSS has an especial trim mechanisim by rotating the mast. In the tested condition a rotation of $\beta=70°$ is sufficient to pull one side of the sail straight and by that to maximise the length of the opposite side. A longer adjustment of foot length would result in less mast rotation needed to create this effect. As described in section 4.2 the mast rotation is analysed in increments of $10°$ from $\beta=0°$ to $\beta=50°$. In the flow simulation six cases are exemplarily calculated whereby the AoA of $\alpha=7.3°$ is constant.

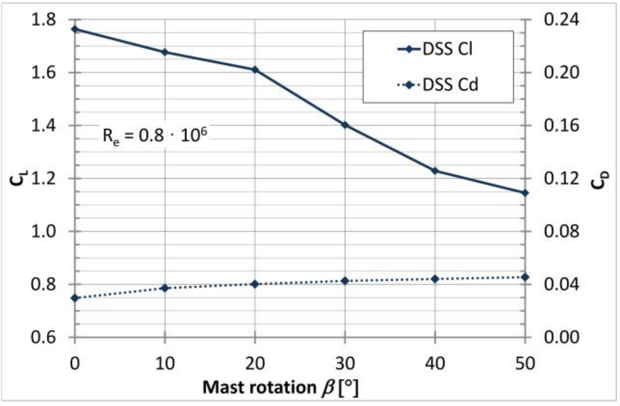

Figure 9: C_L and C_D at different mast rotation angles

The lift and drag coefficients at the different mast rotation angles in Fig. 9 show a decreasing performance with rising rotation angles. This is explained by Fig. 10. It can be seen that the thickness rises while the camber decreases. The increase of profile thickness is mainly responsible for the increase in drag, while the decreasing camber reduces the lift of an aerodynamic profile. [5].

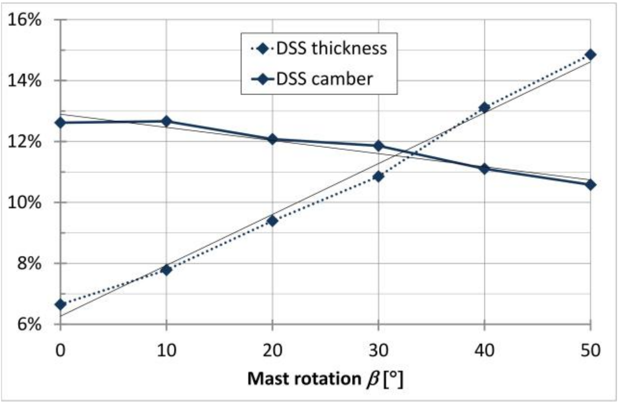

Figure 10: Geometric variation by mast rotation angle

It also has to be remembered that these effects depend on the Reynolds number and respectively the wind speed.
In full-scale when all trim mechanisms can be used together camber and thickness can be adjusted separately from each other. This is supposed to be a great advantage over single surface sails and wing sails. None of which has the capability to change their profile thickness.

6 CONCLUSIONS

The aims of the study were to draw up a conceptual design of a DSS and to analysis its viability in terms of structural behaviour and potential performance. Therefore qualitative wind tunnel tests with a quasi 2D profile section were conducted and the resulting shapes were analysed by a 2D fluid simulation.

The qualitative wind tunnel tests showed a good-natured and stabile standing sail section. The principal functionality is assured and realisable. The presented sail system showed good aerodynamic characteristics in the 2D flow simulation and a high performance potential.

It becomes apparent that the trim mechanism of mast rotation is an influential device by allowing the DSS to vary its profile thickness. That is a unique characteristic compared to conventional single surface sails and wing sails. Considering probable weight and cost no significant disadvantages compared to already applied sail systems are expected. The intended simple structure of the DSS should result in user-friendly handling.

This study investigates the concept for a 2D section. Further CFD studies in 3D at different Reynolds numbers and model tests are needed to make reliable statements about the structural stability and performance. Thereby the optimal trim could be detected and a more practical comparison could be made. Moreover downwind conditions should also be investigated.

7 REFERENCES

1. Milidragovic, M., ‘WING SAIL AND METHODE OF USE’, United States Patent Nr: 5868092, 1999.

2. Freistadt, W., Freistadt, O., ‘PROFILSEGEL‘, Patentschrift Nr: 463701, 1928.

3. Trost, M. D., VARIABLE CAMBER INFATABLE AIRFOIL, United States Patent Nr: 5671690, 1997

4. Lyngholm, T., ‘WING PROFILE SAIL’, United States Patent Nr: 6141809, 2000

5. Marchaj, C.A., ‘AERO-HYDRODYNAMICS OF SAILING’, *Granada Publishing*, 1979

6. Maughmer, M. D. and Princeton University, ‘A COMPARISON OF THE AERODYNAMIC CHARACTERISTICS OF EIGHT SAILWING AIRFOIL SECTIONS’, *Technical report*, 1979.

7. Hansen, H., ‘ENHANCED WIND TUNNEL TECHNIQUES AND AERODYNAMIC FORCE MODEL FOR YACHT SAILS’, *PhD thesis, The University of Auckland*, 2006

8. Drela, M., Youngren, H., ‘XFOIL 6.9 USER GUIDE’, http://web.mit.edu/drela/Public/web/xfoil/xfoil_doc.txt (22.04.2013), 2001

9. Abbott, I.H. and Doenhoff, A.E., ‘THEORY OF WING SECTIONS’, *Dover Publications Inc.*, 1959

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