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SYSTEM OF AERODYNAMIC STABILIZATION OF A MONOHULL SAIL BOAT

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SUMMARY

In this paper a construction principle of an aerodynamic heel stabilization system of a sailing yacht is reviewed. It is based on the patent DE № 198 54 872. The advantages of the new mean of heel stabilization are shown compared to the common ballast based stabilization of a yacht in regard to high speed and safety of sailing under extreme conditions.

The qualitative analysis of the performance of the aerodynamic stabilization system AIST in this article is preliminary and evaluative. Final conclusions of the efficiency of the AIST system can be made on the basis of experimental aerodynamic research, a control system simulation and a testing of an experimental model with the system of aerodynamic heel stabilization.

1. INTRODUCTION

High speed and sailing safety are among the most important characteristics of sailing yacht quality, constantly being in the specialists' focus of interest. "As sailing boats don't move with a constant velocity in contrary to aircrafts, but sail relative to the wind under changing directions and wind conditions reaching from calm sea to storms, it is not to be expected that a simple criterion can be used to estimate the characteristics of the rig or the hull." [1]

The required driving force and the corresponding sail carrying capacity of the sailing boat depend on the stability of the yacht on all courses and at all wind speeds. One distinguishes between static and dynamic stability. The static or metacentric stability is the ability of a yacht to balance back to the original equilibrium state following the effects of the hydrostatic buoyancy force and the gravity force under the influences of disturbing forces and moments. The dynamic stability of a monohull sail boat is the ability of a yacht to return to the original state after disturbing influences in a process of aperiodic or periodic oscillating motion.

The static stability of a monohull sail boat is ensured by the optimal choice of the hull shape (stability by form) and the use of the ballast, usually adjusted on the fixed or on the so-called canting-keel. The ballast weight can amount up to 70% and more of the total yacht weight. It increases the draught and correspondingly the hydrodynamic resistance of the yacht. At present the following constructing parameters are mainly optimised during planning and building of sailing boats: displacement, sail carrying capacity, weight of the hull, rigging and ballast, and the allocation of the ballast.

Yet, it is known [1] that the maximum possible speed a sailing yacht can reach is the higher the lighter it is, the smaller the displacement-to-length-ratio and the bigger the sail area-to-displacement-ratio are. Therefore it is important to develop means and facilities to ensure the stability of monohull sail boats that have to be light, work reliably under all applicable conditions, speeds and wind directions, provide sailing safety at high sail boat velocities, simplicity and usability of its control, and a high comfort on board.

2. AERODYNAMIC STABILIZATION OF THE SAILING BOAT HEEL

The method and facility of aerodynamic stabilization of the sail boat heel are described in the patent № 198 54 872, German Patent Office [2]. The aerodynamic intelligent stabilizer AIST is an aerodynamic aerofoil, which is attached to the masthead by hinges, Figure 1.

The hinges permit an angular movement relative to the three perpendicular axes. By means of a manual or automatic control, the aerofoil orientates itself in the horizontal plane, independently of the angular position of the sail boat and its mast with the maximum possible angle of attack to the relative wind speed. Acting through the hinges on the mast like on a lever, the aerofoil produces an aerodynamic righting moment and counteracts the heel moment.

Figure 2 shows the scheme of the equilibrium of forces acting on the sail boat with a system of aerodynamic stabilization. The value of the aerodynamic righting moment is proportional to the square of the air flow velocity and to the angle of yacht heeling. In other words – the heel moment caused by the pressure of the air flow on the sail is compensated by the stabilizing facility which interacts with the air flow and produces an aerodynamic moment that counteracts the heel moment. This method of boat stabilization can be considered as an active stabilisation.

Table 1: Boat specifications

LOA	8. 7 m	Sail area	45 m²
BOA	2.0 m	Aerofoil area	6 m²
Draft	1.8 m	Aerofoil elevation	16 m
DSPL	950 kg		
Mast height	14 m	Crew	225 kg
Ballast	300 kg		

The aerofoil of the stabilizer is mounted on the highest point of the yacht, in a height, where the speed of the atmospheric wind, in compliance with the wind gradient, reaches its maximum. The conditions of the airflow around the aerofoil of the stabilizer are similar to the conditions of the airflow around the glider aerofoil. Therefore the aerodynamic efficiency of the aerofoil of the stabilizer, the lift-to-aerodynamic drag-ratio, A/D_A can be on the same level as for the glider aerofoil (40-60). This is a substantially greater value than the aerodynamic efficiency of the currently used sail constructions. The set of the sailing boat components – aerodynamic stabilizer, sails, and hull are similar to the aerodynamic components of an aircraft of a classical aerodynamic scheme, Figure 3.

The aerofoil of the aircraft produces an aerodynamic lift keeping the aircraft in the air, where the point of application of the lifting force is behind the aircraft's centre of gravity and causes a nose-down moment. This moment is countered by a nose-up moment produced by the negative lift of the tail plane, located at the fuselage rear at the maximum distance from the centre of gravity. Similarly to the aircraft's aerofoil, the yacht sail produces an aerodynamic force, causing a heeling moment which is usually counteracted by the righting moment due to the margin of the static (metacentric) stability of the yacht, Figure 2. On a yacht using the system of aerodynamic stabilization, the necessary righting moment is produced by the aerodynamic stabilizer and at the expense of the metacentric stability. At a high relative wind speed V_A and yacht velocity V_S the aerodynamic righting moment of the stabilizer can be much higher than the static righting moment. This way, the aerodynamic heel stabilizer increases the similarity of the yacht and the aircraft and verifies the statement: *"A sailboat is not only a boat, but a combination of a boat and an aeroplane"* [1]

Let's consider the interaction of the static and aerodynamic stabilities of the yacht and their influence on the characteristics of the overall stability of the sail boat. Figure 2 shows a scheme of the static balance of forces which affect the sail boat with the aerodynamic stabilization of heel. Figure 4 shows the simulations of stability of a cruiser sail boat as an example. The boat specifications are given in Table.1 and the initial data for calculations in Table.2.

Table 2: Initial data of the sail boat stability

Aerofoil:	
Area, m2	6
Wingspan, m	8
Angle of attack, (°)	18°
Aerodynamic lift coefficient, C_A	2
Fastening height of the aerofoil, m	16
Metacentric height, GM, м	1

The total static stability of the sail boat with the AIST-System is the sum of the metacentric righting moment and the aerodynamic righting moment of the AIST-System which compensate together the heel moment of the boat.

$$M_X = M_{st} + M_A - M_K \quad (1)$$

$$M_{ST} = WGM \sin\varphi \quad (2a)$$

$$M_A = AH \sin\varphi \quad (2b)$$

$$MK = F_K a \quad (2c)$$

$$M_X = WGM \sin\varphi - F_K a = 0 \quad (3)$$

where

M_{ST}	hydrostatic righting moment
M_A	aerodynamic righting moment of AIST
M_K	heel moment of the boat due to action of the sail heel force ($F_K = C_K q S_A$)
q	velocity pressure of the air flow
S_A	sail area
C_K	aerodynamic coefficient of the sail heel force
A	aerodynamic lift of the aerofoil ($A = C_A q A_S$)
C_A	aerodynamic coefficient of the lift
A_S	aerofoil area
W	boat weight ($W = mg$)
H	distance from the centre of fastening of the aerofoil to the rotation axis of the boat, X
GM	metacentric height
a	arm of couple F_K and F_S producing the heel moment
φ	heel angle of the boat

As follows from the given diagram, the amount of the aerodynamic righting moment M_A strongly rises with the increase of the relative wind speed V_A and its value becomes even greater than the static metacentric stability margin of the sail boat. Here, the total righting moment of the sail boat with the AIST-System appreciably increases as compared to common sail boats. The righting aerodynamic moment of the stabilizer increases virtually simultaneously with the increase of the air flow velocity, in other words as fast as the aerodynamic lift changes with the change of the wind velocity.

By optimizing the design parameters of the stabilizer – arrangement height, aerofoil area and its aerodynamic characteristics – it is possible to change essentially the available overall stability without constructive changes of the hull and without a displacement increase of the sail boat.

3. EXPERIMENTAL VALIDATION

A model was built for the validation of the functioning principle of the aerodynamic stabilizer (Figure 6). The model consists of an aerodynamic aerofoil connected by a hinge with one degree of freedom to a rod simulating the mast. The rod is attached by hinges to a frame that is mounted on a car roof. By means of a semirevolving system of cable transmission, the aerofoil angle of attack remained the same independently of the rod's angle of inclination. The necessary velocity of the air flow was set by the choice of the car speed. The car speed (air flow velocity), the raising angle of the rod, and the angle of the attack were recorded. The model specifications are presented in Table.3.

Table 3: Test model specifications

Mast simulator:	
Height, m	0.9
Diameter, mm	8
Aerofoil:	
Area, m2	0.12
Area, m2	1.22
Wing section	S 4083 mod.
Angle of attack, (°)	18°

The experiment proved the efficiency of the functioning mode of the aerodynamic stabilizer. The aerofoil with the "mast" always rose from an inclination of 60° to a practically vertical state (angle of inclination: 2°-3°), and remained in this position despite an increasing car speed, Figure 6. Obviously, the aerofoil raising angle is a function of its aerodynamic efficiency. Neglecting the aerodynamic drag of the rod -"mast", transmission components and fastening elements, the maximal value of the angle of the aerofoil raising is evaluated in theory according to its aerodynamic polar chart:

$$\frac{C_A}{C_{DA}} = tg(90 - \varphi)\,, \tag{4}$$

where

C_A aerodynamic coefficient of the lift
C_{Da} aerodynamic drag coefficient

The absence of a limitation in terms of wind speed is a very important feature of AIST, as the stabilizer has to fulfil its functional task during all sailing conditions of the boat, in contrary to a sail that can be removed or reduced in its area etc.

4. AERODYNAMIC HEEL STABILIZATION AND STATIC STABILITY OF A SAIL BOAT DURING ROUGH SEA

The boat stability during rough sea differs considerably from the static stability determined by calculation for the case of calm sea [3]. There is a known phenomenon described in [3] – the knockdown of a yacht even on the crest of a smooth wave. The reason is a decrease in yacht weight during the lift on the wave crest.

This phenomenon is due to the appearance of the centrifugal accelerations a as a result of circular rotation of the water particles in the wave [1]. At the wave crest the resultant acceleration of the boat with mass m is equal to $(g - a)$, at the wave trough it is equal to $(g + a)$, where g is the gravitational acceleration.

Respectively, the static stability of the boat at the wave crest is:

$$M_{ST} = m(g - a)GM \sin\varphi \tag{5}$$

at the wave trough:

$$M_{ST} = m(g + a)GM \sin\varphi \tag{6}$$

At the same time the hydrostatic stability margin of the yacht decreases, as it is proportional to the yacht weight at its given metacentric height, Figure 7.

As the total moment which compensates the heel moment of the boat is the sum of the metacentric moment and the aerodynamic moment of the stabilizer (Equation 1), the total stability moment, despite of the decrease of the static moment, allows to avoid the knockdown of the boat due to relatively large value of the aerodynamic righting moment of the stabilizer (Figure 4).

$$M_{Xsum} = m(g - a)GM \sin\varphi + AH \sin\varphi \tag{7}$$

The righting moment of the aerodynamic stabilizer doesn't depend on the parameters of the waves or orbital currents affecting the underbody of the yacht, but only on the wind velocity and the angular position of the boat.

If the sail area is too large at rough sea and waves are flooding the deck, there are sudden conditions when the sailing boat turns end over end. The aerodynamic stabilizer can essentially reduce the risk of the pitchpole. As it follows from Figure 10, the aerodynamic moment counters the overturning moment [4].

$$M_A = AH \sin \psi \tag{8}$$

The value of the stabilizing moment could be evaluated from diagrams representing a change of the aerodynamic righting moment of the stabilizer evaluated for the heel of the sail boat at different wind speeds (Figure 4). It's correct as the moment of the stabilizer does not depend on the design factor of the boat hull. As it follows from diagrams, the value of the righting moment may be equal to or even more then the metacentric stabilizing moment. The ability of the stabilizer to keep the yacht afloat depends on the speed of the airflow around the aerofoil and the angle ψ. The pitchpole hazard exists mainly for ocean yachts, where the stabilizer could be practically the only mean to decrease the pitchpole moment and to increase the safety of sailing under such extreme conditions.

5. AERODYNAMIC STABILIZATION OF THE HEEL AND ROLLING

Atmospheric and hydrodynamic disturbing forces and moments could be considered as accidental impacts forcing changes of the kinematic parameters of the sail boat. These disturbances could generate the roll motion relative to the longitudinal axis of the boat which causes not only discomfort to crew and passengers but also increases the hazard of knockdown of the boat. In this context, the dynamic stability of the boat, i.e. its ability to dampen the roll is a very important characteristic defining the sailing safety.

It is very dangerous to sail by the lee during fresh breezes and following sea. It increases the rhythmic roll and the tendency to knockdown which is typical not only for a small racing dinghy, but for all sail boats [1],[3]. The wind force causes the rolling not only during stiff breezes but also at moderate wind speeds. This problem is in strong interconnection with the sail area-to-displacement-ratio. In combination with an insufficient moment of inertia, a light draught and an ineffective hydrodynamic hull damping, this can lead to a strong and possibly catastrophic knockdown. The rolling occurs if the angle of the relative wind and the sailing course is between 120° and 195°. If the boat starts to roll, and it doesn't matter how small it is, the rolling rig itself produces the periodically changing air forces which amplify and maintain the roll motion [1]. The aerodynamic stabilizer acts in this case as an aerodynamic damper.

There are two possible versions of stabilizer control:

a) The stabilizer aerofoil is held in a horizontal position against the direction of the relative wind. The heel moment is compensated by the righting moment of the stabilizer, Figure 8a, whose value depends on the value of the angle of heel.

b) The aerofoil of the stabilizer is deflected aside opposed to the occurring heel. The value of the righting moment in this case is substantially bigger and depends to less extent on the yacht heel, Figure 8b.

AIST's advantage lies in its practically instantaneous response to occurring disturbances both in the automatic and manual control mode. Under the real state of sea the boat is exposed to a great extent to hydrodynamically induced rolling, which can lead to fatal wave rolling [3]. As it follows from the scheme presented in [3], the margin of the static stability increases the heel of the yacht. This effect is even more significant for light modern yachts with a relatively small displacement.

The system of aerodynamic stabilization AIST increases the overall yacht stability in all considered cases. The only requirement is a sufficient airflow velocity over the stabilizer. In other words, the aerodynamic stabilizer is a universal tool of stabilization which is able to counter the roll arising from a non-uniform stalling airflow around the sails (Karman vortex street) and from the hydrodynamic forcing of the waves. At a sail boat heel relative to the longitudinal axis with the angular velocity ω_x, the stabilizer aerofoil produces an additional lift which increases the stabilizing moment of AIST. This additional moment which depends on the angular velocity, is directed in such a way that it decreases the angular velocity of the roll and is therefore a dampening moment.

It is considered that the disturbance acts upon the boat and causes the increment of the motion parameters only until the initial time t_0. The response of the sail boat to external influences could be presented in this case as a natural vibration motion. The natural vibrations of the sail boat relative to the longitudinal axis could be simplified and expressed as equation [1]:

$$\varphi = \varphi_0 e^{\frac{-b_R t}{2I_x}} \cos \omega_x t \tag{9}$$

where:

φ_0	initial amplitude
b_R	resultant damping coefficient
I_X	moment of inertia relative to the longitudinal axis
ω_X	roll frequency
t	time

The system is dynamic stable if:

$$b_R = b_H + b_A > 0 \qquad (10)$$

where:

b_H hydrodynamic damping coefficient

b_A aerodynamic damping coefficient

If the resulting damping coefficient is positive, it means that the roll motion is decaying and its amplitude is decreasing. As the hydrodynamic damping coefficient is usually positive, it depends on the value of the aerodynamic damping coefficient which value becomes the resultant damping coefficient - whether positive or negative one.

The aerodynamic damping coefficient for a sail boat with the AIST-System consists of two components: aerodynamic forces and moments which are produced by the sail, and aerodynamic forces and moments which are produced by the aerodynamic stabilizer. At the sailing by the lee the sail does not dampen but, on the contrary, produces the roll motion.

$$M_{XD}(\omega_X) = M_{XH}(\omega_X) + M_{XS}(\omega_X) + M_{XA}(\omega_X) \qquad (11)$$

$$b_R \sim f\left\{\frac{\partial M_{XS}(\omega_X)}{\partial \omega_X}\right\} \qquad (12)$$

Taking into account the heel angular velocity, the aerodynamic stabilizer moment of forces which after the proper transforms is one of the components of the aerodynamic damping coefficient $b_{A,}$ can be expressed as:

$$M_{XA}(\omega_X) = AH\sin(\varphi + \delta) \qquad (13)$$

where:

$$A = C_A \varphi \frac{V_R^{\,2}}{2} A_S \qquad (14)$$

At the boat rotation with an angular velocity ω_X, the speed of the air flow V_r flowing around the aerofoil rises:

$$\overline{V}_R = \overline{V}_H + \overline{V} \qquad (15)$$

$$V_R^{\,2} = V_H^{\,2} + V^2 \qquad (16)$$

where:

$$V = \omega_X H \qquad (17)$$

Accordingly, the moment of the stabilizer, which dampens the roll, increases.

$$\begin{aligned} M_{XA}(\omega_X) &= C_A \varphi \frac{V_A^{\,2}}{2}\; S_{AH} + si\omega n(\varphi + \delta) \\ &\quad + C_A \varphi \frac{\omega^2 H^2}{2} S_{AH} \sin(\varphi + \delta) \end{aligned} \qquad (18)$$

The increment of the stabilizer moment can be estimated in Figure 4. For example, at a heel angle of 15° and a wind speed of 25 kn the moment of the stabilizer equals 4000 Nm. The velocity increase of the air flow to 30 kn at the expense of the angular velocity ω_X at the same heel angle of 15° gives rise to the stabilizing moment up to 6000 Nm. The dampening component of the stabilizing moment amounts to 2000 Nm. In exactly the same way, the stabilizer dampens disturbances caused with a sudden velocity increase (squalls). The stabilizing moment goes up simultaneously with the wind velocity increase. In this case it is safe to say that the AIST-System compensates the disturbances in proportion to the angular acceleration of the sail boat.

The moment of the aerodynamic stabilizer, which value depends on the design factor, its arrangement height above the line of rotation, the area of the aerofoil and its aerodynamic efficiency, could be chosen sufficiently great in order to efficiently dampen together with the hydrodynamic forces the sail induced rolling. Under deflection of the aerodynamic stabilizer aerofoil relative to the top of the mast δ as shown in Figure 8, and under the condition of a fast response of the control system AIST or of a quick response of a crewman performing the manual control, the disturbance could be counteracted at the very beginning of the roll motion when the amplitude and the angle velocity are still not great. Thus, a quick-operating active control of the aerofoil of the stabilizer is an effective method to avoid the dangerous roll motion of the sail boat.

6. EFFECT OF THE AERODYNAMIC HEEL STABILIZATION ON THE YACHT SPEED ABILITY

The high-speed of the sail boat depends on the sail carrying capacity characterized by the sail area-to-displacement-ratio. The striving for enhancement of the sail driving force leads to an increase of the heel force and accordingly to an increase of the heel moment that causes the problem of ensuring the transverse stability. Therefore the high speed of the sail boat is determined to a great extent by its transverse stability margin. The use of the aerodynamic heel stabilizer allows to enhance substantially the necessary transverse stability of the yacht and respectively the relative driving force of the sail at high speeds of the relative wind V_A without increasing the displacement, the dimensions, and as a consequence the hydrodynamic resistance. The higher the driving force of the sail, the higher is in theory the attainable speed. To illustrate the effect of the AIST-System upon the augmentation of the sail carrying capacity, the speed limitation due to the growth of the hydrodynamic resistance and the performance of the underbody, etc. are disregarded in this example. The assessment criterion is the value of the driving force of the sail-to-displacement-ratio, F_R/Δ, which is a main attribute of the available sail carrying capacity.

Let's examine this on the following example. Two implementations of the sail boat with the same design objectives, at a constant close-hauled course angle and a constant heel angle will be compared. The first one is equipped with a common rig, the second one – with the aerodynamic stabilizer AIST. A high relative wind speed and a high angle of heel are characteristic for the close-hauled course.

We assume that the yacht is moving with a heel of 25° (an angle of heel greater than 25° leads to a harsh increase of the hydrodynamic resistance). With a corresponding choice of the shape of the underbody of the yacht, the hydrodynamic resistance doesn't change significantly at heel angles between 0° and 25°. Furthermore we also assume that the angle of sail inclination, its aerodynamic efficiency, the lift-to-aerodynamic drag-ratio, $L/D=12$, and the course angle of the yacht $\gamma_A=30°$ don't change. The stabilizer aerofoil is always oriented in a horizontal position and its aerodynamic lift A produces the righting moment M_A. With an increase of the relative wind velocity V_A it's assumed that the sail area changes so that aerodynamic heel force F_K is maximal, determined by the overall stability margin of the yacht.

From the moment sum equation (3), it follows that:

$$F_K = \frac{WGM \sin\varphi + AH \sin\varphi}{a} \quad (19)$$

It is obvious from Figure 2 that the driving force of the sail is:

$$F_R = F_K \cot(90° - \gamma_A + \cot^{-1} L/D) \quad (20)$$

With a course angle $\gamma_A=30°$ and a sail aerodynamic efficiency $L/D = 12$

$$\cot(90° - \gamma_A + \cot^{-1} L/D) = 0.47 \quad (21)$$

Knowing the limit value F_K, it is possible to evaluate the value of the maximal available driving force of the sail. Figure 5a shows the diagram of available righting moments depending on the relative wind speed V_A at an angle of heel of $\varphi=25°$. The boat moment without the aerodynamic stabilizer does not depend on the wind speed and it is depicted as a straight horizontal line. The aerodynamic and the total moments of the boat with the AIST-System rise with the square of the wind speed and are theoretically unrestricted. (Naturally, there are strengthening, hydrodynamic etc. restrictions which are not considered in this example.)

Figure 5b presents the available heel force of the sail and its driving force, calculated with maximal values of the total righting moment shown in Figure 5a.

Figure 5c shows the available relative driving and heeling forces of the boat, with and without the AIST-System. As it follows from these diagrams, the available driving force grows steadily with the increase of the wind speed. This analysis confirms that it is possible to design a sailing boat which will be able to reach a record high speed and even to plane at all points of sailing including the close-hauled course. As the increase of the driving force takes place without an increase of the yacht weight (e.g. at the expense of the ballast), it allows to design a sail boat with a small displacement and a big overall stability that is able to plane at all points of sailing including the close-hauled course. Here a "true" plane means that the following criteria are fulfilled: The plane is a sailing condition where 50% to 90 % of the forces that counteract the weight are produced by hydrodynamic reacting forces; the rest is the hydrostatic uplift force. In general the full plane is reached at a velocity-length-ratio $V_S/\sqrt{L} \geq 5.43$ [1].

An appreciably greater righting moment can be produced by the aerodynamic heel stabilizer at the close-hauled course (when the yacht heel moment reaches its maximum compared to other courses relative to the wind) if it is inclined in the direction opposed to the boat heel thus increasing the effective lever arm, Figure 9. Here a component of the lifting force of the stabilizer occurs directed against the yacht movement (much as a control of airplane, Figure 3, where the elevator produces a negative lift, diminishing the total lift force of airplane). This component's value is noticeably smaller than the driving force of the sail F_R and therefore its influence on the speed ability of the yacht is insignificant. This method of stabilizer control allows to keep the yacht closer to the vertical position, in addition improving the aerodynamic performance of the sail (the lift coefficient C_L and at the same time the lift force L and the driving force of the sail F_R are increased), which in turn contributes to an increase of the yacht speed at a close-hauled course.

7. CONCLUSIONS

The sailing boat aerodynamic heel stabilizer is an active system of stabilization which produces a righting moment using the wind power and compensates at the same time to a great extent the heeling moment due to the wind pressure on the sail of the boat. The greater the relative wind speed, the greater is the righting moment of the AIST-System. Thereby it differs from the passive means of heel stabilization at the expense of ballast and of geometry of the hull, where design factors are chosen at the design phase and don't depend on the wind speed that produces the boat heel.

The application of the AIST aerodynamic heel stabilizer enables to increase appreciably the total stability of the boat especially during moderate and strong wind, to reduce the weight of the ballast or to abandon it completely. The AIST-System makes it possible to increase the relative driving force of the sail F_R/Δ at a close-hauled course by several times, compared to the conventional sail boats with the passive means of heel stabilization, due to an increase of the sail area-to-displacement-ratio and a decrease of the displacement-to-length-ratio. It leads respectively to the substantial improvement of the velocity and dynamic performances of the sail boat.

The AIST-System enhances the safety of sailing as it provides an active aerodynamic control developing a moment which dampens oscillations and counteracts the roll motion of the sail boat arising from a non-uniform stalling airflow around the sails (Karman vortex street) at a close-hauled course or from hydrodynamic effects. The aerodynamic stabilizer could be useful in extreme sailing conditions in order to reduce the hazard of the pitchpole during rough sea. The AIST-System is also effective under the drastic wind impacts or under the change of the wind speed and direction as the heel compensating aerodynamic moment increases virtually simultaneously with the increase in wind speed and immediately at the beginning of the initial heel angle change as the finite increments of the angular velocity of the heel and its angle still equal to zero. This feature to practically instantly dissipate the disturbing pulse of the aerodynamic energy, at least partially, ensures a powerful dampening of the angular disturbances of the sail boat. With the subsequent heel angle increase, the compensative aerodynamic moment increases additionally in proportion to the deflection angle. Thus the magnitude of the moment of the stabilizer depends on the wind speed, the angle of heel and the design factor of the AIST-System such as the size of the aerofoil, its aerodynamic efficiency, and its arrangement height above the line of rotation of the sail boat.

The control of the AIST-System could be implemented as a manual system, under the simple sailing condition, or as a completely automatic one combining both manual and automatic control and including sensors to measure the kinematic data of the boat, angles of attack of the aerofoil, speed and direction of the wind as well as servo drives, a control unit with computer, and a power supply unit.

Application of the AIST-System enables to design a light high-speed sail boat using the current technology of the aeronautical materials and the technological advance in the field of the automatic control of the aircrafts. The sail boat could reach a record speed at a close-hauled course and even plane ensuring a reliable safety of sailing. Such a sail boat with the system of the aerodynamic stabilization would be an aesthetically beautiful eye-catcher while sailing.

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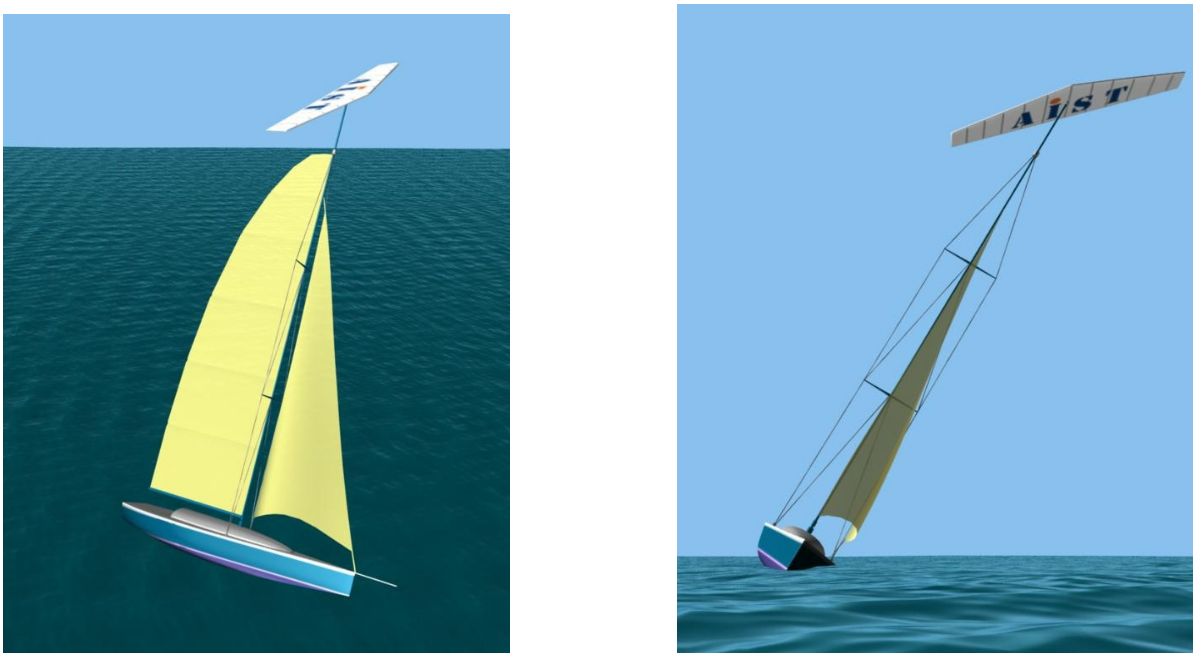


Figure 1 - General view of a sail boat with a system of aerodynamic heel stabilization AIST.

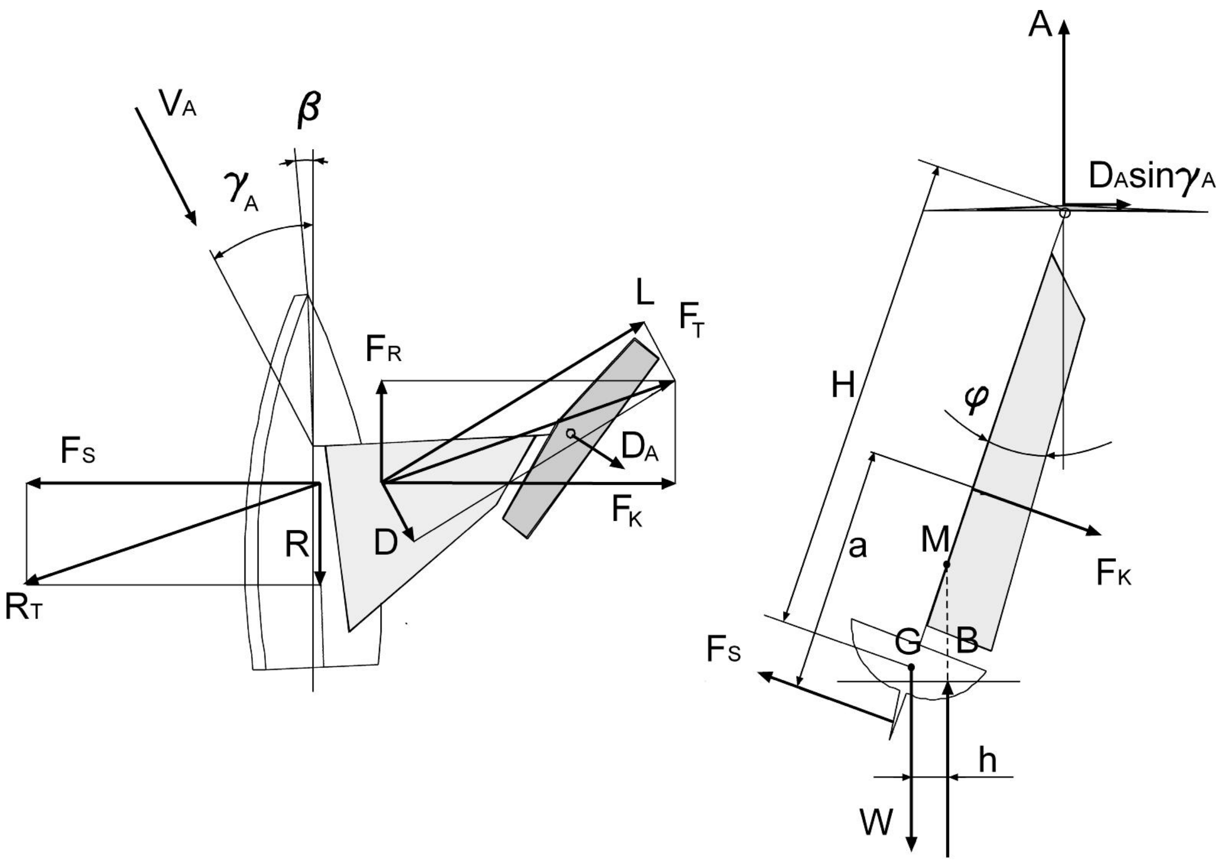


Figure 2 - Scheme of the static equilibrium of forces acting on the sail boat with a system of aerodynamic heel stabilization AIST

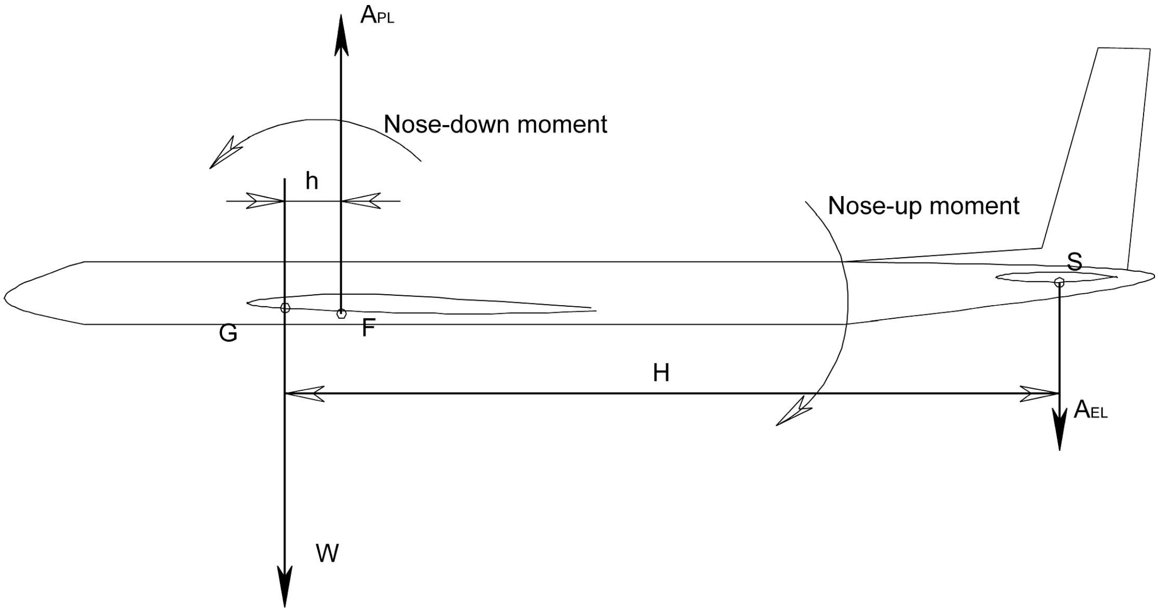


Figure 3 - Scheme of forces acting on an aircraft in flight

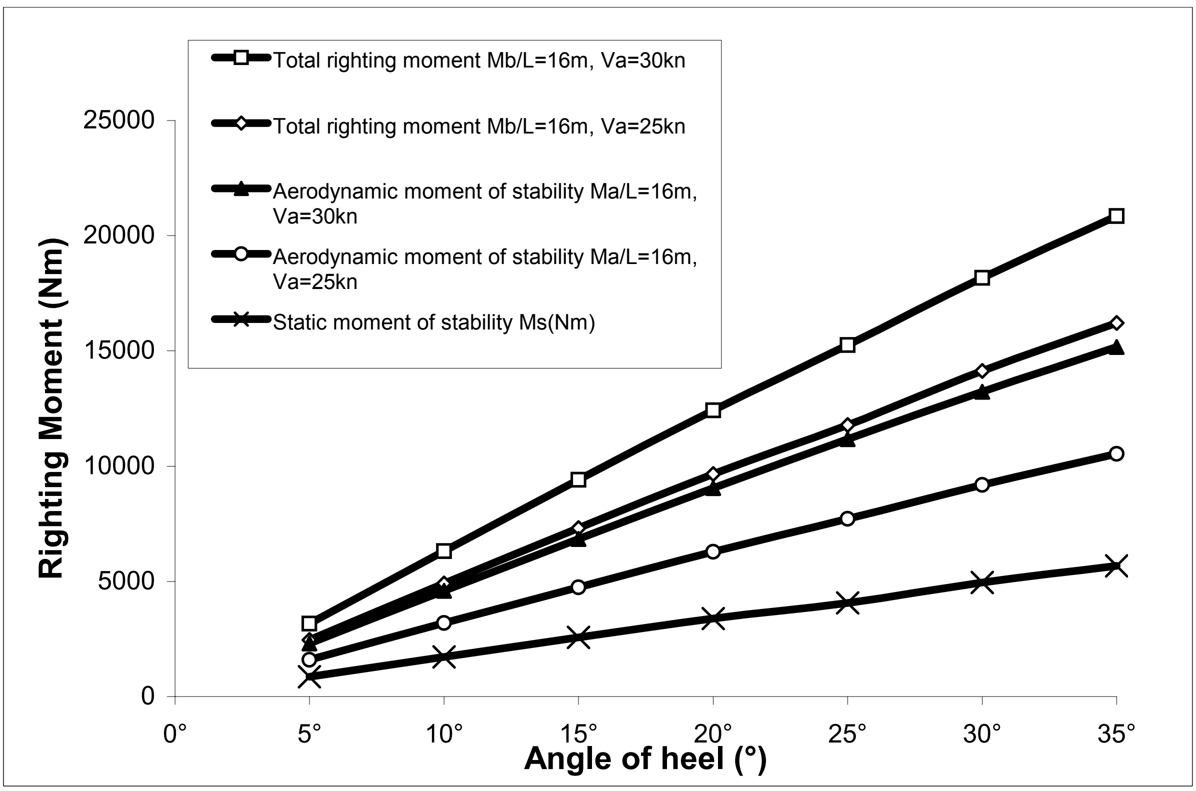


Figure 4 - Static and aerodynamic righting moments of a sail boat depending on relative wind speed and heel angle

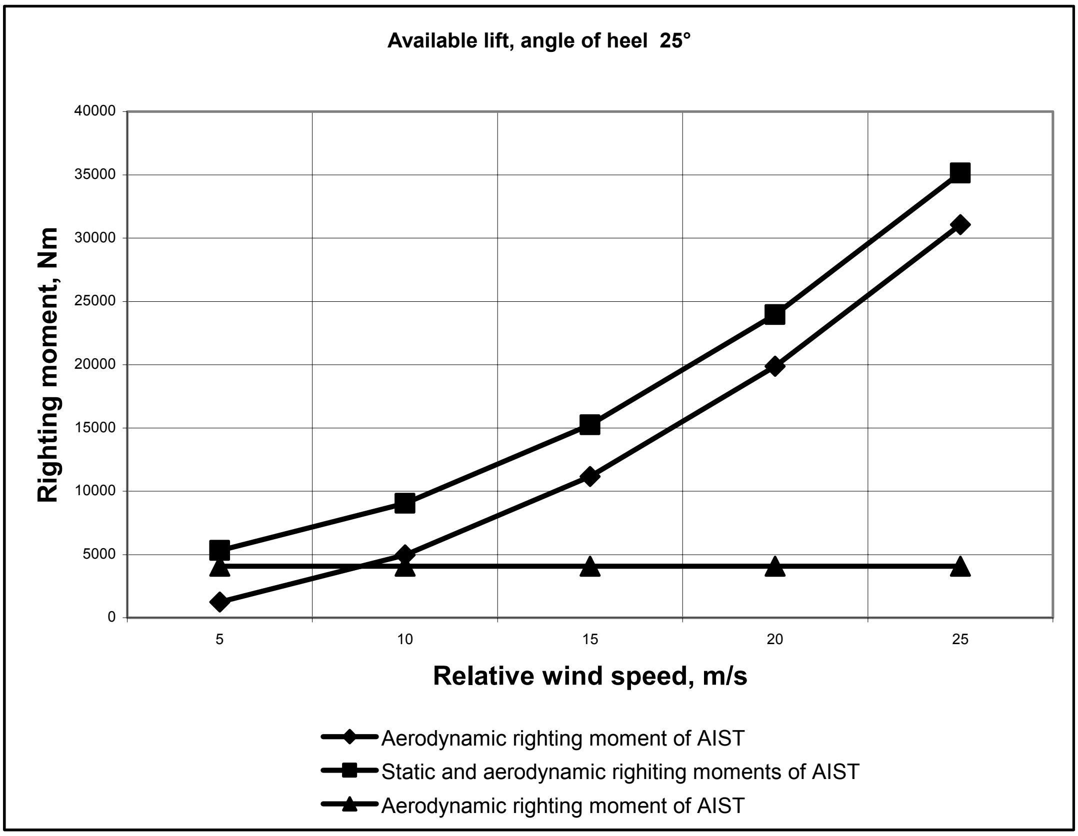


Figure 5 a - Static and dynamic righting moments as well as heeling and driving forces of the sail depending on the relative wind speed at a constant angle of heel φ=25°

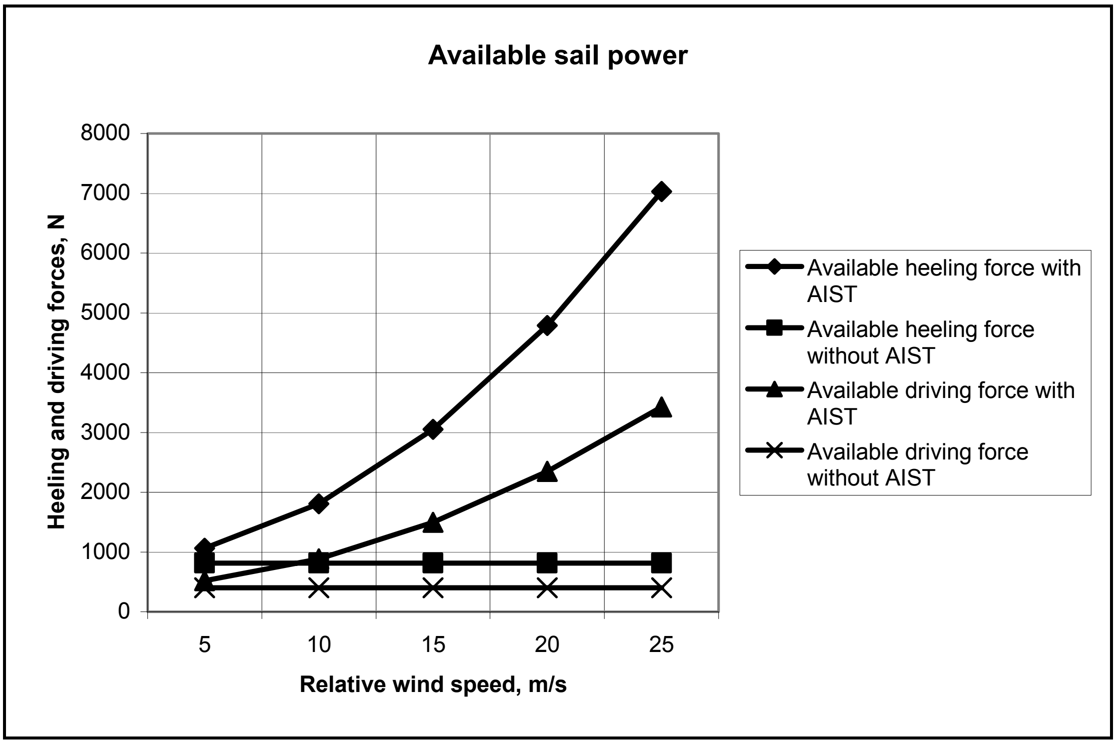


Figure 5 b - Static and dynamic righting moments as well as heeling and driving forces of the sail depending on the relative wind speed at a constant angle of heel φ=25°

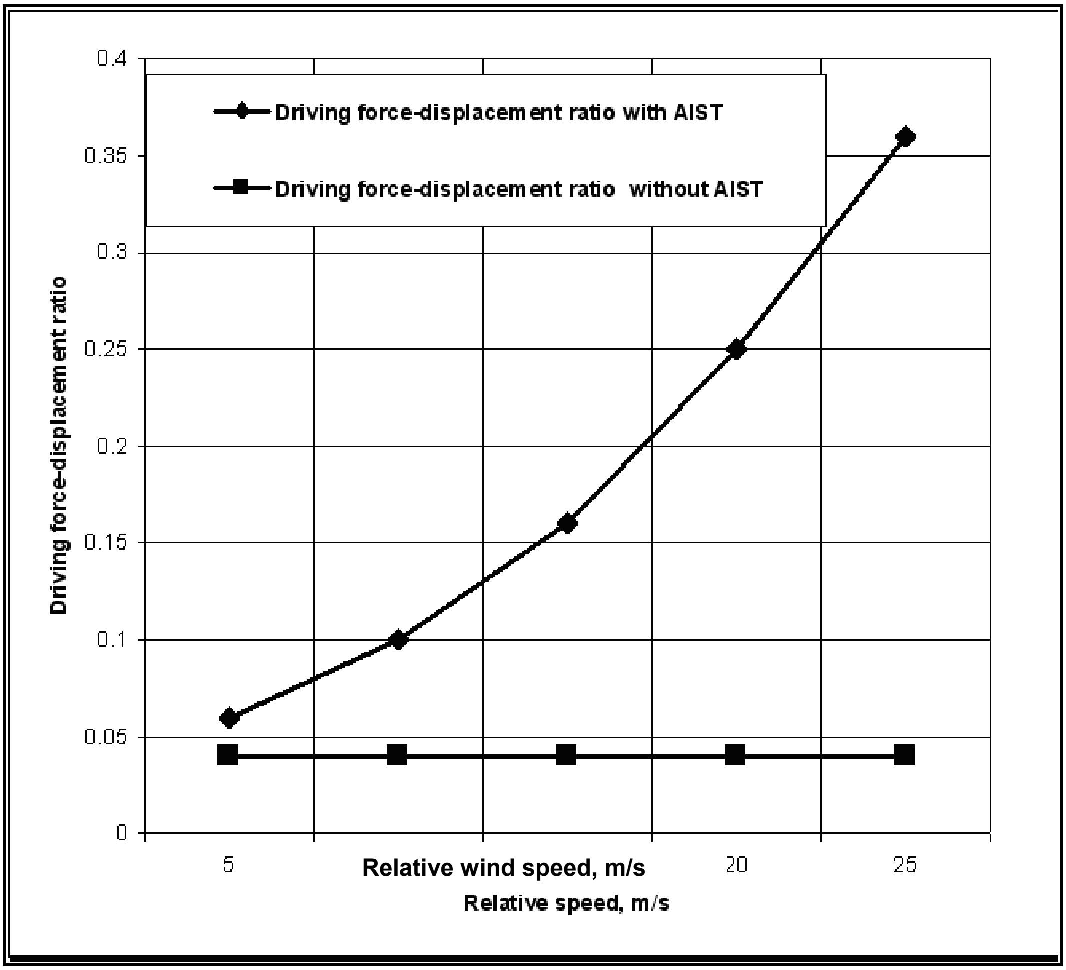


Figure 5 c - Static and dynamic righting moments as well as heeling and driving forces of the sail depending on the relative wind speed at a constant angle of heel φ=25°

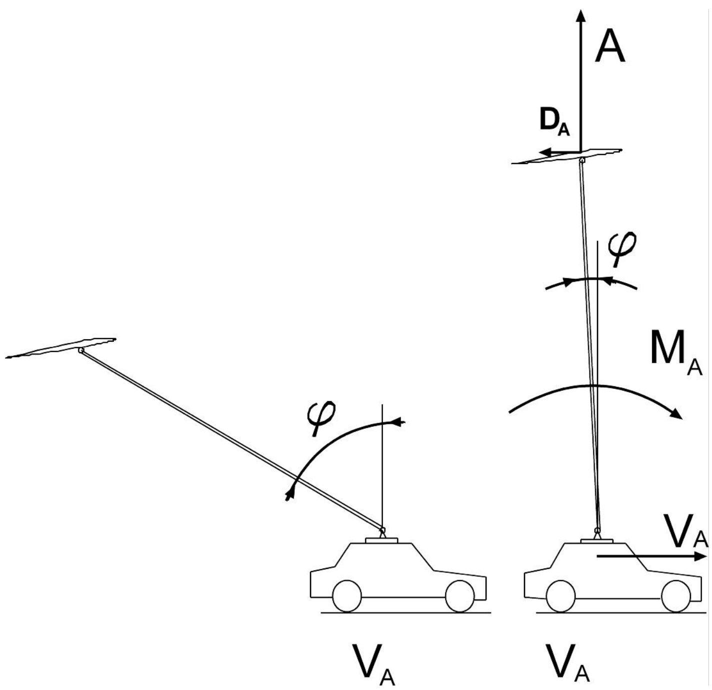


Figure 6 - Scheme of the experimental validation of the functioning principle of the aerodynamic

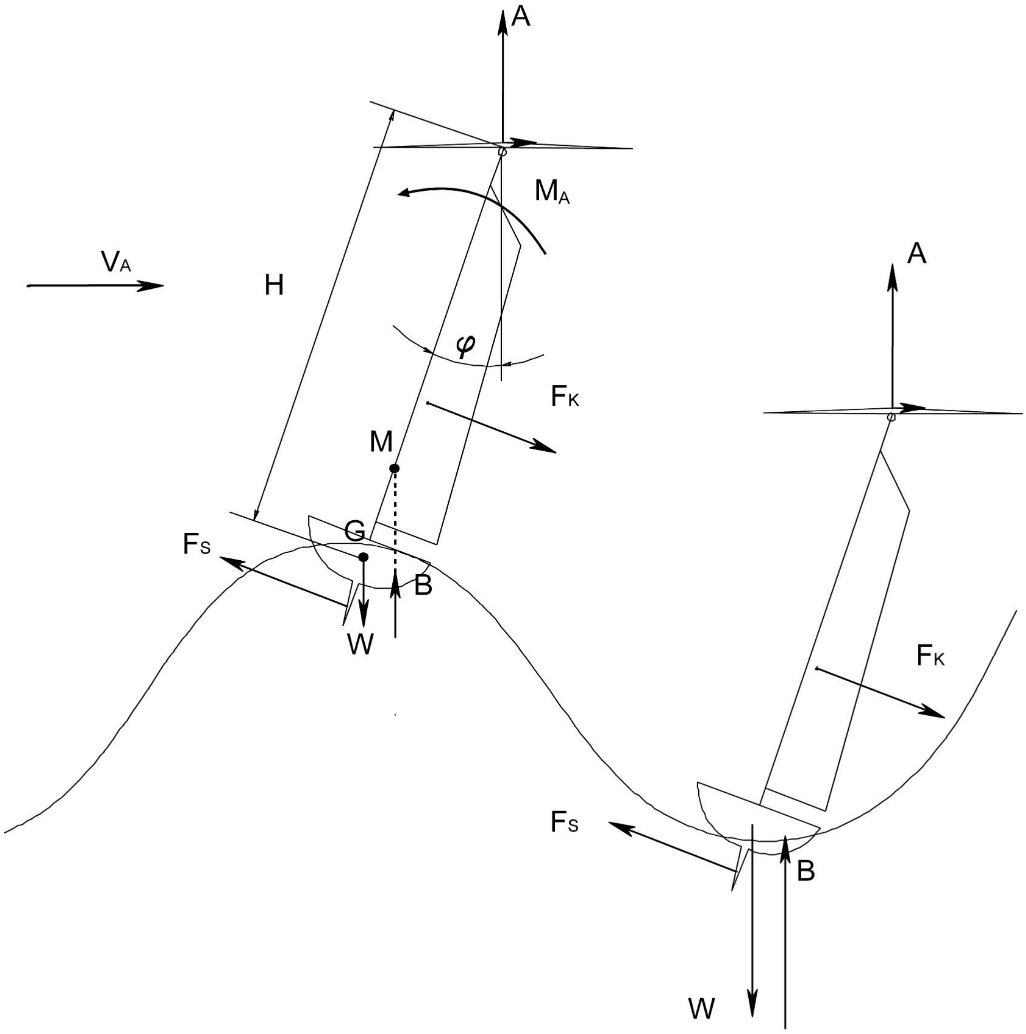
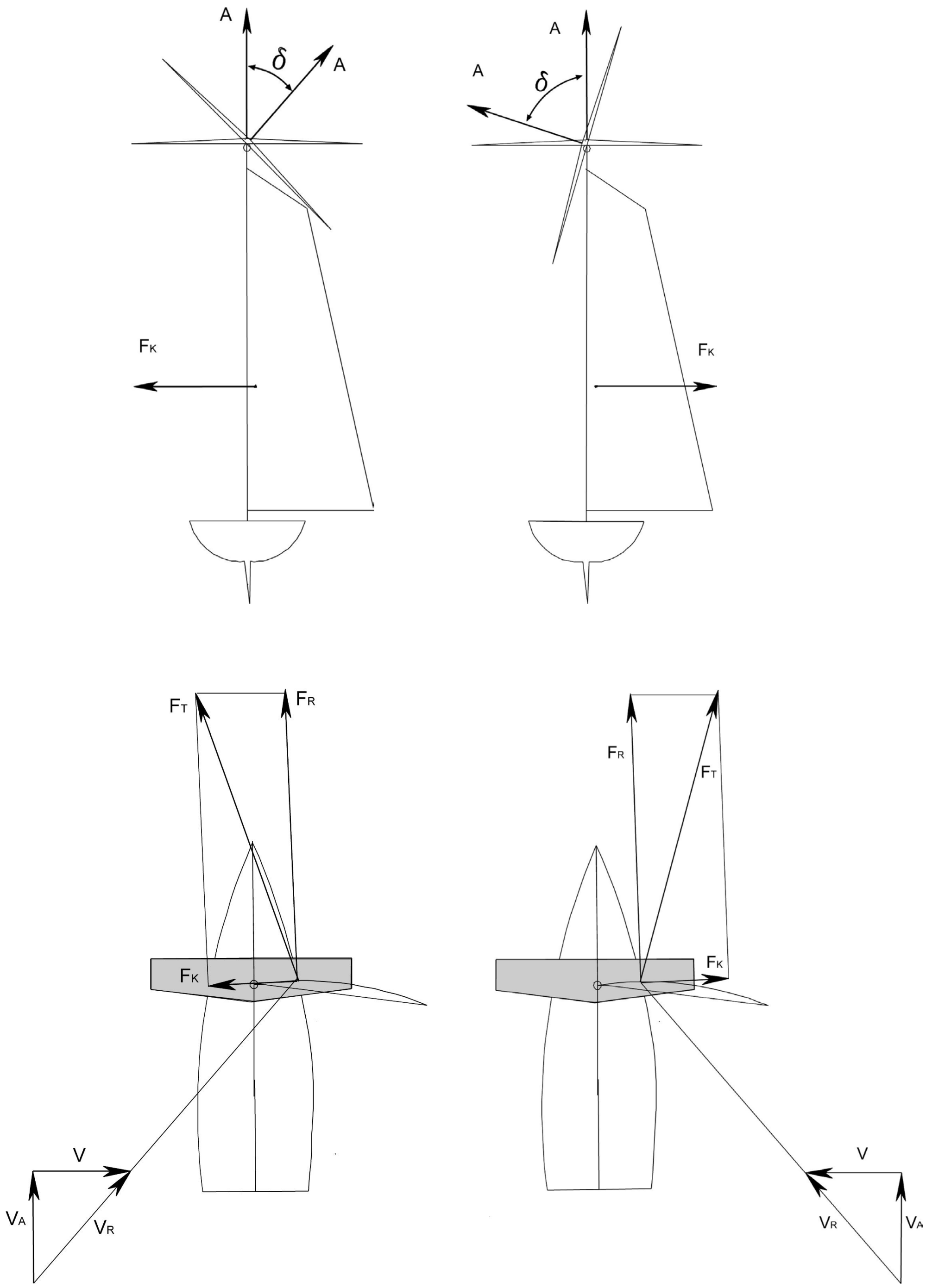


Figure 7 - Scheme of the forces appearing due to the wave impact on a sailing boat with a system of aerodynamic stabilization AIST.



(a) (b)

Figure 8 - Scheme of the aerodynamic stabilizer control for roll prevention.

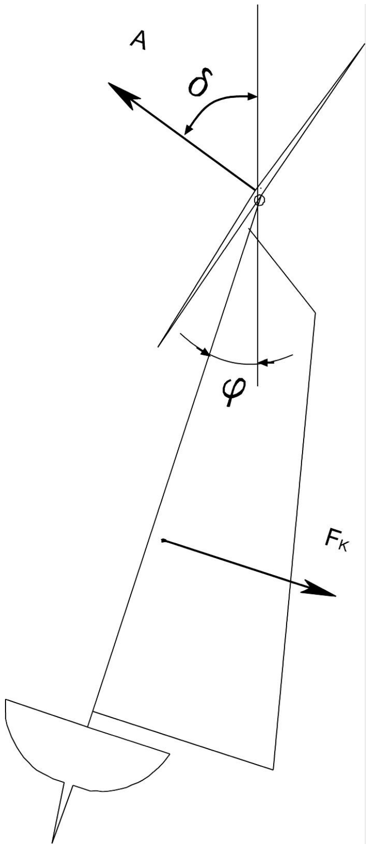


Figure 9- Scheme of the aerodynamic stabilizer control at the close-hauled course.