Points of force application to the oar and efficiency of various blade designs

Report on research project

1. Acknowledgments

This research project was kindly supported by Australian Institute of Sport and Mr. Stuart Wilson of Sykes Rasing Boats, Geelong, Australia

2. Introduction

Location of the points of force application to the oar in rowing is interesting because it defines an actual gearing ratio, which is very important for both training and racing. The force is applied to the oar at three points: the handle, gate and blade. While location of the gate force is quite obvious (at the projection of the center of the pin), location of two other forces may vary for the following reasons:

- Rower may apply handle force more with inside or outside arm in sweep rowing, which may shift the point of the centre of the force within 20-30cm. In sculling, the centre point is more definite, but even there it may vary within 5-6cm because of shift of the fingers on the handle.
- Position of the centre of the blade force may vary because of various blade shapes and hydrodynamics of the blade at various phases of the drive.

Determination of the exact location of the centres of the force is also important for accurate calculation of the blade propulsive efficiency (Affeld et al, 1993, Kleshnev 1999).

An attempt to determine the centre of blade force was made in canoeing by Aitken and Neal (1992). A system was developed to quantify the on-water forces, impulse, and power generated by a kayak paddler. They glued strain-gauges at two different locations of the paddle shaft and tried to determine the centre of pressure on the blade by means of comparison of readings from these two sensors.

We repeated this method in a pilot study and found that it doesn't work in principle. The reason was that the readings on both sensors are proportional to the torque, so their ratio is constant at any position of the force application. When we applied less force at longer lever or more force at shorter lever, the ratio of the signals was the same

To overcome this problem, we developed a system, which measure both force (independently on its lever) and its torque (product of the force by its lever). Comparison of signals from two sensors of force F and torque M allowed us to determine the lever L of the force using equation:

$$L = M / F$$

This was done for both handle and the blade. To check the accuracy and derive the total balance of the forces on the oar, we also measured two forces at the gate (actually on the pin): normal and axial to the oar shaft.

3. Methods

3.1. Equipment

A radio telemetry system was used for data acquisition. The system consisted of transducers, an electronic unit with signal conditioners and analogue-to-digital converters (12–bit, 25 Hz sampling frequency), and a pair of radio modems. The total mass of the recording and transmitting parts of the system (which were placed in the boat) was less than 1 kg. Acquired data was transmitted to a motor-boat and stored in real time on the hard disc of a laptop computer. The total mass of the boat with riggers and the telemetry system, but without the moveable seat, was estimated for each session.

Several relevant mechanical parameters were measured. Boat velocity (Vb) was measured using an electromagnetic impeller (Nielsen-Kellerman, Boothwyn, PA, USA) which was linked to the telemetry system. The impeller was calibrated during each session by timing the boat over a known distance. The linear calibration regression was calculated using at least two different average boat speeds (accuracy ±1.0%).

Boat acceleration (Ab) was measured along the horizontal axis using an accelerometer (Analog Devices, Norwood, MA, USA; accuracy ±1%). The accelerometer was calibrated using three-point linear regression, where the horizontal orientation of the accelerometer was taken as zero and the vertical orientations of the accelerometer in opposite directions were taken as ±g = 9.796 m•s-2 (Geoscience Australia). The accelerometer was built into the electronics unit, mounted on the boat deck, and aligned along the boat's longitudinal axis. Positive acceleration was taken to be towards the bow of the boat (i.e. when the boat increases its velocity).

The horizontal (θ) and vertical (β) oar angles were measured using conductive-plastic potentiometers (linearity ±0.1%) connected to the oar shaft with a light arm and a bracket. The oar angles were calibrated at four or more points using a protractor.

Seat position (Ls) was measured using a custom-made device, which consisted of a spring-loaded 10-turn potentiometer connected to the seat with a low-stretch line (accuracy ±0.1%). The position of the top of the trunk (Lt) was measured in small boats using a device similar to the seat position sensor. The device was attached to the boat deck and the line was passed up through a pulley mounted on a mast and attached to the trunk of the athlete, level with the sternum and clavicle (C7) joint.

3.2. Instrumented Oar and Gate

The total six channels of force and torques were measured on each oar-gate:

1. Handle force ***Fh*** (Figure 1) was measured using instrumented oar handle with binocular-shape cut and glued strain-gauges. This design makes the force reading independent on the point of the force application at the handle;
2. Torque of the handle force Mh was measured using strain-gauges glued on the inboard of the oar shaft close to the sleeve and button;
3. Torque of the blade force Mb was measured using strain-gauges glued on the outboard of the oar shaft close to the sleeve;
4. Blade force ***Fb*** was measured using binocular-shape cut with glued strain-gauges close to the blade. This design makes the force reading independent on the point of the force application at the blade;
5. Pin force ***Fpn*** normal to the oar shaft was measured using instrumented oar gate with strain-gauges glued onto rotating pin;
6. Pin force ***Fpa*** papallel (axial) to the oar shaft was measured instrumented oar gate with strain-gauges glued onto rotating pin.

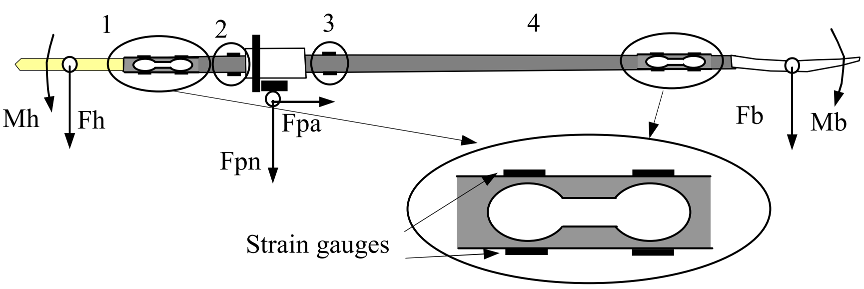


Figure 1. Scheme of forces and torques measurement at the oar-gate.

Each instrumented channel was dynamically calibrated before each session using a precision load cell to apply a load to the handle (Figure 1). The oar was supported 0.02 m from the collar (at the point corresponding to the centre of contact with the gate), the blade was fixed, and the force applied perpendicularly to the oar shaft at the middle of the handle (0.15 m in from the end for a sweep oar; 0.06 m for a sculling oar).

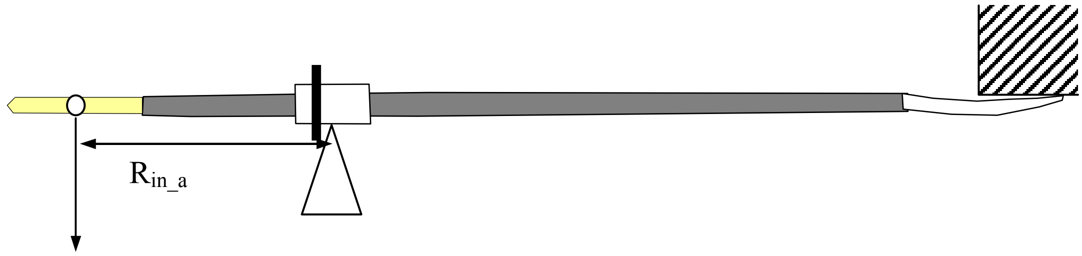


Figure 2. Calibration method

3.3. Subject and test protocol

A male rower participated in the study (age 28 years, height 1.90m, weight 89.0kg). He performed three sets of four test trials in single scull. Distance of each trial was 250m with approximately 2 min. recovery time. The target stroke rates during each trial were 20, 24, 28 and 32 min^{-1}. Three different types of blades were used for each trial:

- 1st set - Smothie with vortex;
- 2nd set - Big blade;
- 3rd set - Big blade with vortex.

3.4. Data processing

The data was collected and stored in PC and then processed using special software. The data of all stroke cycles of each trial was normalised and averaged and average (typical) data arrays were produced for each primary variable. Then typical arrays of derived variables were calculated (e.g.: power variable was derived from the force and velocity variables, etc.). Both primary and derived variables were used for calculation of the single value or discrete variables (e.g.: catch angle was derived as the minimal measured angle of the oar, etc.).

3.5. Graphs:

All graphs represent typical (average) data arrays for each trial.

7. Ratio of the Blade to the Handle *Rb/h* forces was calculated as:
   $Rb/h = \mathbf{Fb_y} / \mathbf{Fh_y}$
   Higher Rb/h means more blade force at the same handle force. This means centre of pressure at the blade closer to inner edge, i.e. shorter outboard.
8. Vertical oar angle *Av* (degrees) was measured at the gate. Zero is an angle corresponding to the position of the middle of the blade at water level. Negative angle is below water level, positive angle is above water level;
9. Waste power *Pw* represents amount of energy spent for slippage of the blade in the water (moving the water mass). It was calculated using the boat velocity, angular oar velocity and the blade force (Kleshnev, 1999). Difference between the handle power *Ph* and *Pw* equal to propulsive power, which moves the rower-boat system:
   $Pp = Ph - Pw$
10. Blade efficiency *Ebl* (%) was calculated as the ratio of the propulsive power *Pp* at the blade to the power applied at the handle *Ph*:
    $Ebl = Pp / Ph$
    Blade efficiency depends on weather conditions (tail wind – higher efficiency, head wind - less efficiency) and many other factors (blade shape, farce application, blade depth, oar angle, boat speed, etc.).
11. Position of the center of pressure at the blade *Lout* (actual outboard length) was calculated using the blade force *Fb* and torque at the blade *Mb*, which was measured directly:
    $Lout = Mb / Fb$
    It is difficult to define an absolute value of the center of pressure at this stage (torque measurement needs to be improved), but difference between the blades should be correct.

3.6. Tables

All discrete data was produced on the basis of typical data arrays.

1. Stroke rate, boat speed and total oar angle are self-explanatory.
2. Effective Angle (degrees) *Aef(d)* is the horizontal angular displacement of the oar when the center of the blade below water level (negative vertical angle). Effective Angle (%) *Aef(%)* is the ratio of *Aef(d)* to the total angle.
3. Average handle, gate and blade forces were calculated per the drive time.
4. Rowing power, waste power and blade efficiency were calculated per the drive time.
5. Wind direction and wind speed were measured relative to the boat. Wind direction was interpreted as the clock face: 0 or 12- head wind, 6-tail wind ,3- wind from bow side, 9- wind from stroke side.
6. Drag factor was calculated as the ratio of the propulsive power and the cube of the boat velocity: $Kd = Pp / v^3$

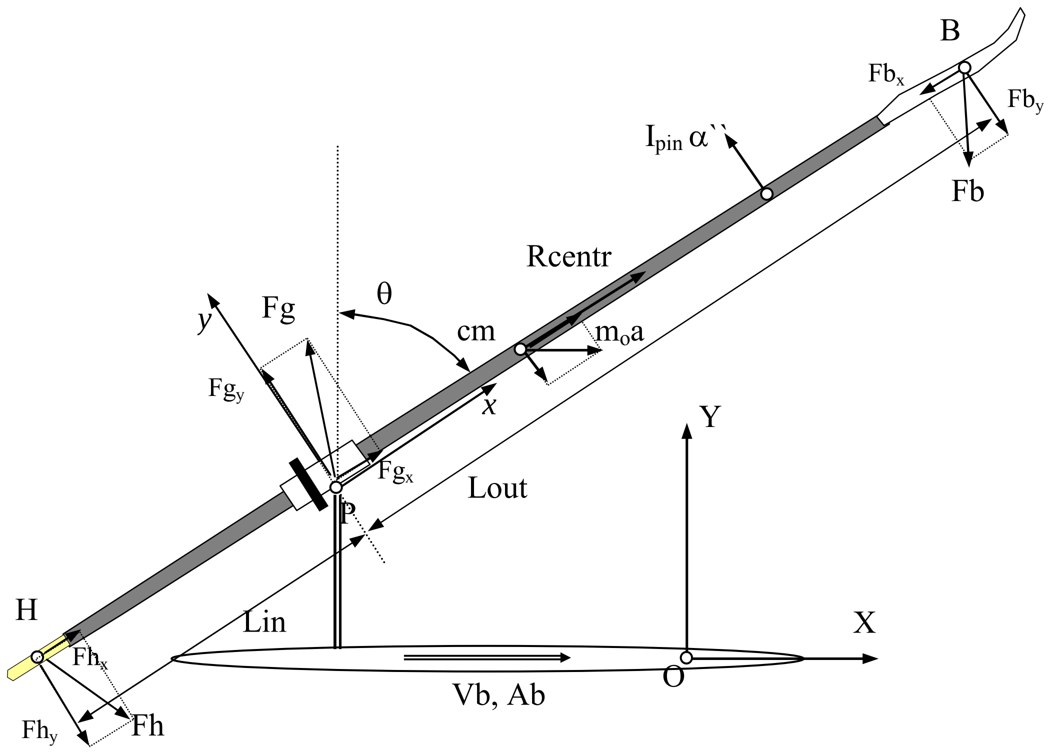


Figure 3. Coordinate system and forces acting on the oar.

4. Results

Unfortunately, we could get correct data only for the right oar. Left oar produced erratic data, when the boat turned over during the first session.

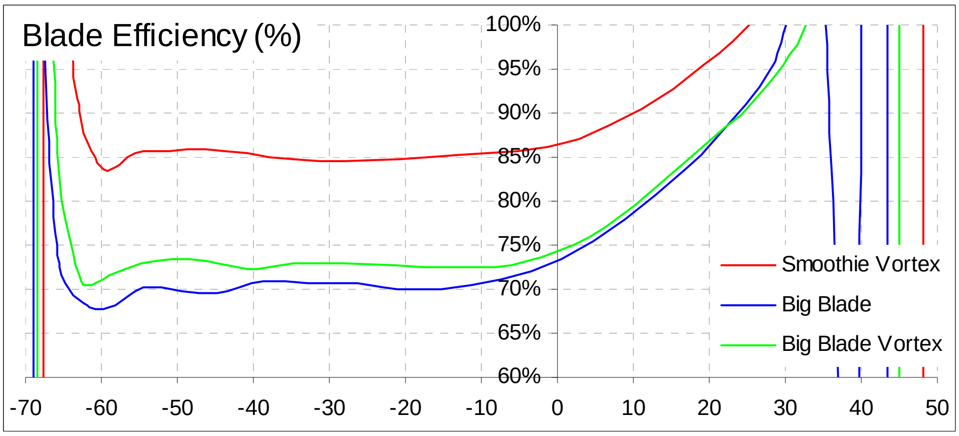
The wind speed and direction appeared to be quite different (tail wind with smoothie-vortex blades and head wind with big blade). Therefore, not all samples were comparable in regards of blade efficiency.

Table 1. Summary

Blade Type	Smoothie Vortex				Big Blade				Big Blade Vortex			
Stroke Rate (1/min)	20.7	24.3	25.9	31.2	20.2	23.8	27.5	31.1	20.6	23.9	25.9	31.4

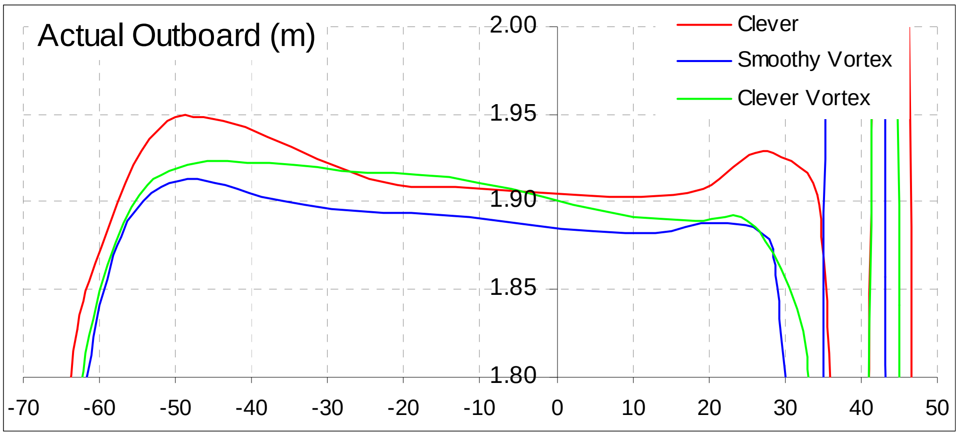
Boat Speed (m/s)	4.37	4.20	4.41	4.55	3.52	3.68	4.31	4.63	3.65	3.79	4.03	4.62
TotalAngle (dg)	116.0	113.2	112.0	108.9	113.6	112.2	110.1	107.8	113.4	110.7	110.1	108.8
Effective Angle (%)	90.9 %	89.0 %	86.2 %	81.8 %	96.6 %	87.7 %	86.9 %	85.6 %	94.0 %	89.2 %	86.0 %	83.8 %
Average Handle Speed (m/s)	1.36	1.42	1.41	1.60	1.30	1.37	1.50	1.60	1.32	1.37	1.39	1.62
Aver. Handle Force (N)	196.8	186.7	209.6	218.1	181.1	202.1	197.6	226.0	192.7	186.5	210.6	226.1
Aver. Gate Force (N)	270.2	259.0	283.4	290.5	245.0	269.4	265.6	300.5	268.3	258.7	287.6	305.0
Aver. Blade Force (N)	83.3	79.9	88.8	92.0	76.6	84.9	84.0	96.9	81.3	77.8	88.2	94.7
Ratio Blade/Handle Forces (%)	42.3 %	42.8 %	42.4 %	42.2 %	42.3 %	42.0 %	42.5 %	42.9 %	42.2 %	41.7 %	41.9 %	41.9 %
Rowing Power (W)	188.4	209.5	239.9	278.3	179.7	220.3	234.9	277.8	184.9	208.8	242.8	298.4
Waste Power (W)	16.7	28.9	26.7	44.3	34.0	42.8	37.1	41.9	32.4	36.5	37.5	47.3
Blade Efficiency (%)	88.0 %	81.5 %	85.0 %	79.4 %	73.8 %	73.6 %	79.1 %	80.5 %	75.7 %	76.1 %	78.8 %	79.2 %
Wind Direction	11.8	11.4	11.7	0.3	11.5	11.9	10.6	11.3	11.3	11.6	11.8	11.4
Wind Speed (m/s)	3.35	2.80	4.00	4.64	6.35	7.27	3.34	3.47	6.00	6.41	6.39	5.09
Drag Factor	1.42	1.65	1.68	1.72	2.08	2.27	1.68	1.67	1.97	2.03	2.00	1.75

At low rate the only comparable trials were 2nd and 3rd (big blade vs. big blade with vortex). Wind speed and direction were very similar (6.00 and 6.25 m/s). Blade efficiency was 1.9% higher with vortex (73.8% and 75.7%), which happened by means of higher efficiency at negative oar angles (from catch till perpendicular). Blade without vortex was a bit more efficient at release.



Rate 20

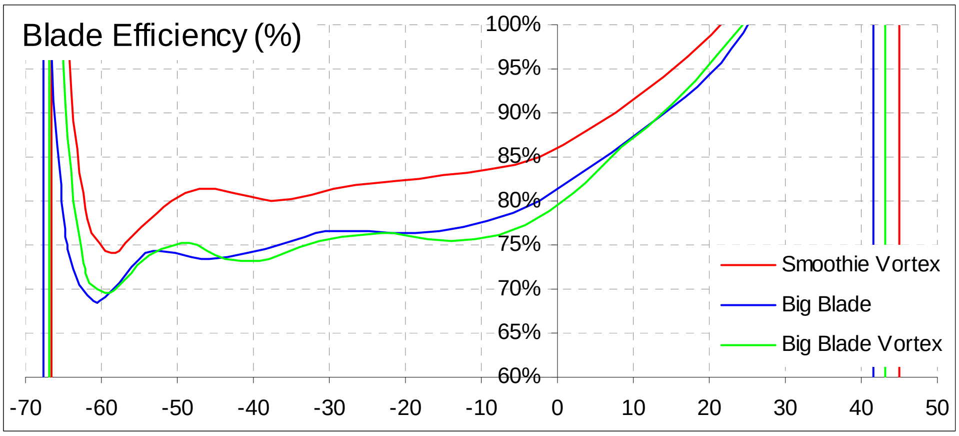
Center of pressure at the blade with vortex was closer to outer edge that corresponds to 2-3cm longer outboard and lower ratio of blade/handle forces:



Rate 20

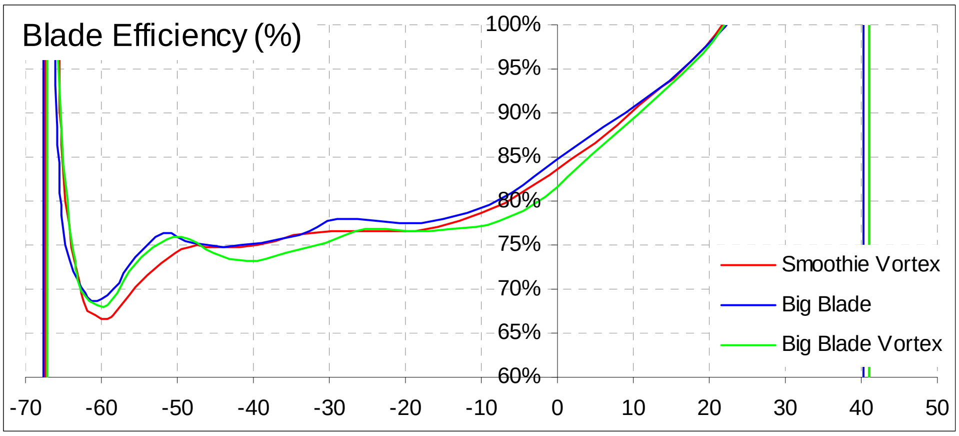
Trials at target rate 24 produced similar results, except the difference in wind speed was a bit higher (7.27 and 6.41 m/s) that caused 2.5% difference in blade efficiency (73.6% with big blade and 76.1% with vortex).

At the stroke rates 26-27 we obtained very close blade efficiencies with both big blades (79.1% and 78.8% with vortex). However, this was achieved at very different wind conditions: side-tail wind with no-vortex (3.34 rel. 4.31 m/s boat speed, drag factor 1.68) and side-head wind with vortex (6.39 m/s, drag 2.00). This clearly shows advantage of the vortex.



Rate 26-27

At the stroke rates 31 we had a light tail wind with big blades (3.47 m/s rel. boat speed 4.63), practically no wind with smoothie vortex (4.64 m/s) and light side-head wind with big-vortex (5.09 m/s). This caused a bit higher blade efficiency with big blade (80.5%) and very similar results with both vortex blades (79.4% smoothie and 79.2% big).



Rate 31

5. Conclusions

- The results of the study show advantage of the vortex blades, which had approximately 2% higher efficiency at comparable wind conditions. This equal to 5-8 s faster times over 2000m race.

- Higher efficiency of the vortex blades happens only between catch and perpendicular oar position.
- Vortex shifts the center of pressure at the blade 2-3 cm towards outer edge that means longer actual outboard leverage and lower blade force at the same handle force.

6. References:

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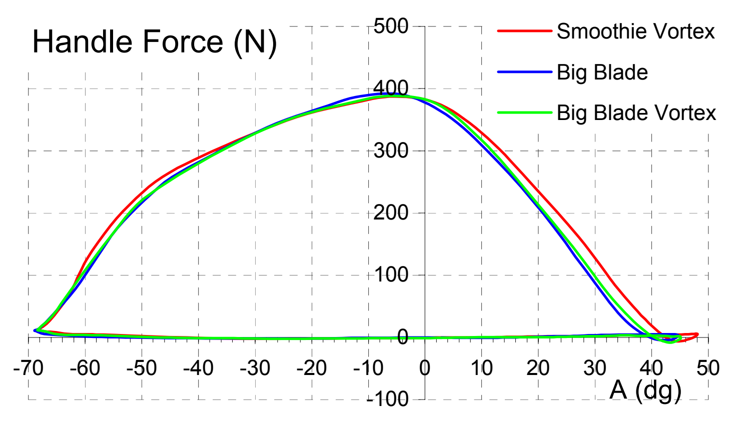
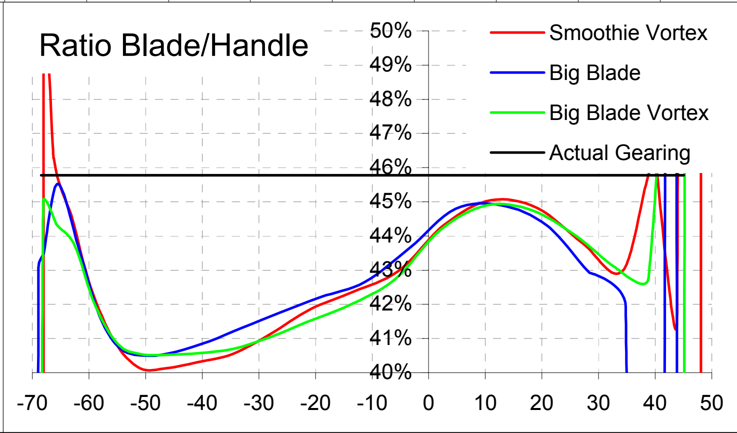
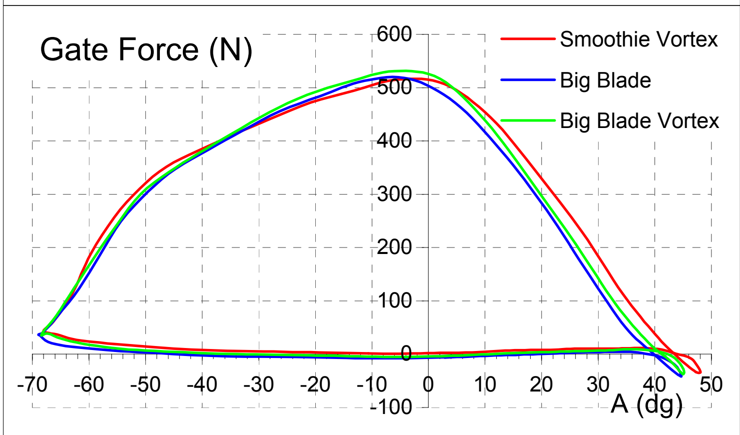
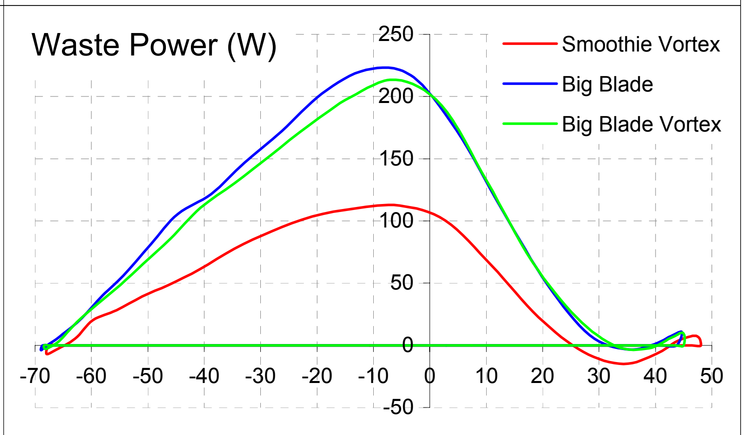
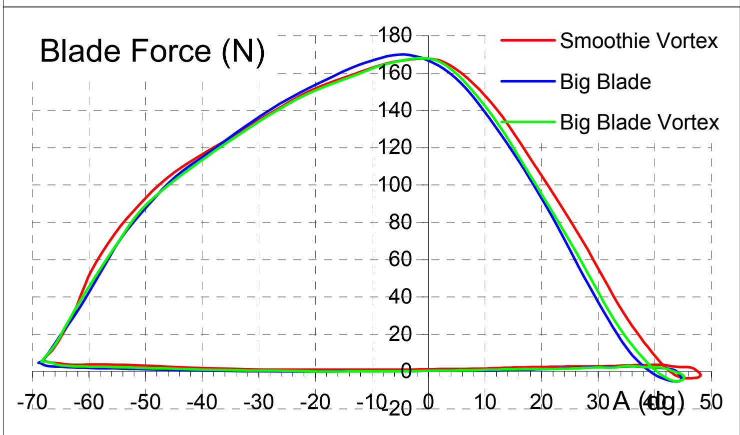
Blade Type	Stroke Rate (1/min)	Boat Speed (m/s)	TotalAngle (dg)	Effective Angle (%)	Average Handle Velocity (m/s)	Aver. Handle Force (N)	Aver. Gate Force (N)	Aver. Blade Force (N)	Ratio Blade/Handle Forces (%)	Rowing Power (W)	Waste Power (W)	Blade Efficiency (%)	Wind Direction (12- head, 6-tail,3-bow, 9-stroke)	Wind Speed (m/s)	Drag Factor
Smoothie Vortex	20.7	4.37	116.0	90.9%	1.36	196.8	270.2	83.3	42.3%	188.4	16.7	88.0%	11.8	3.35	1.42
Big Blade	20.2	3.52	113.6	96.6%	1.30	181.1	245.0	76.6	42.3%	179.7	34.0	73.8%	11.5	6.35	2.08
Big Blade Vortex	20.6	3.65	113.4	94.0%	1.32	192.7	268.3	81.3	42.2%	184.9	32.4	75.7%	11.3	6.00	1.97

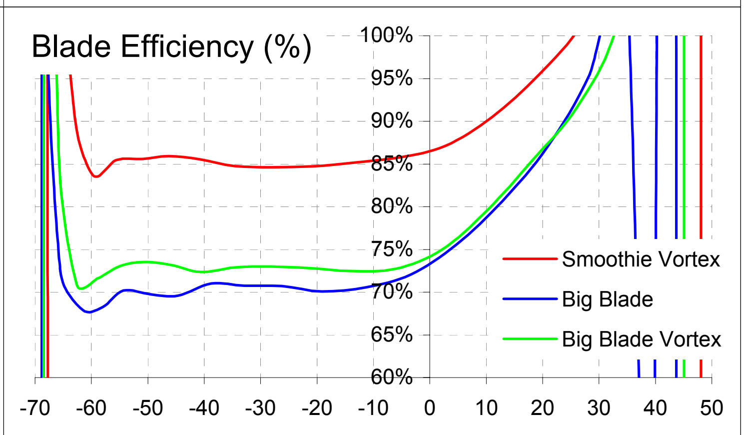


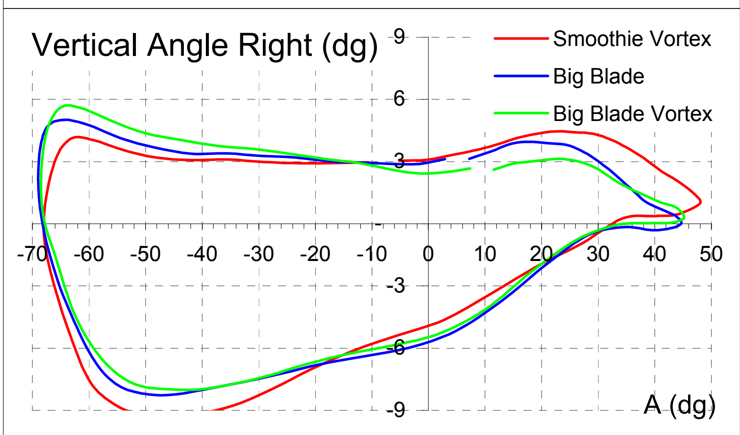


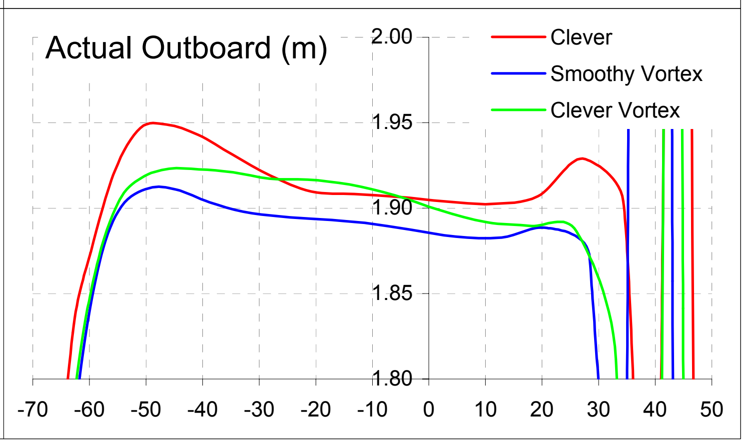












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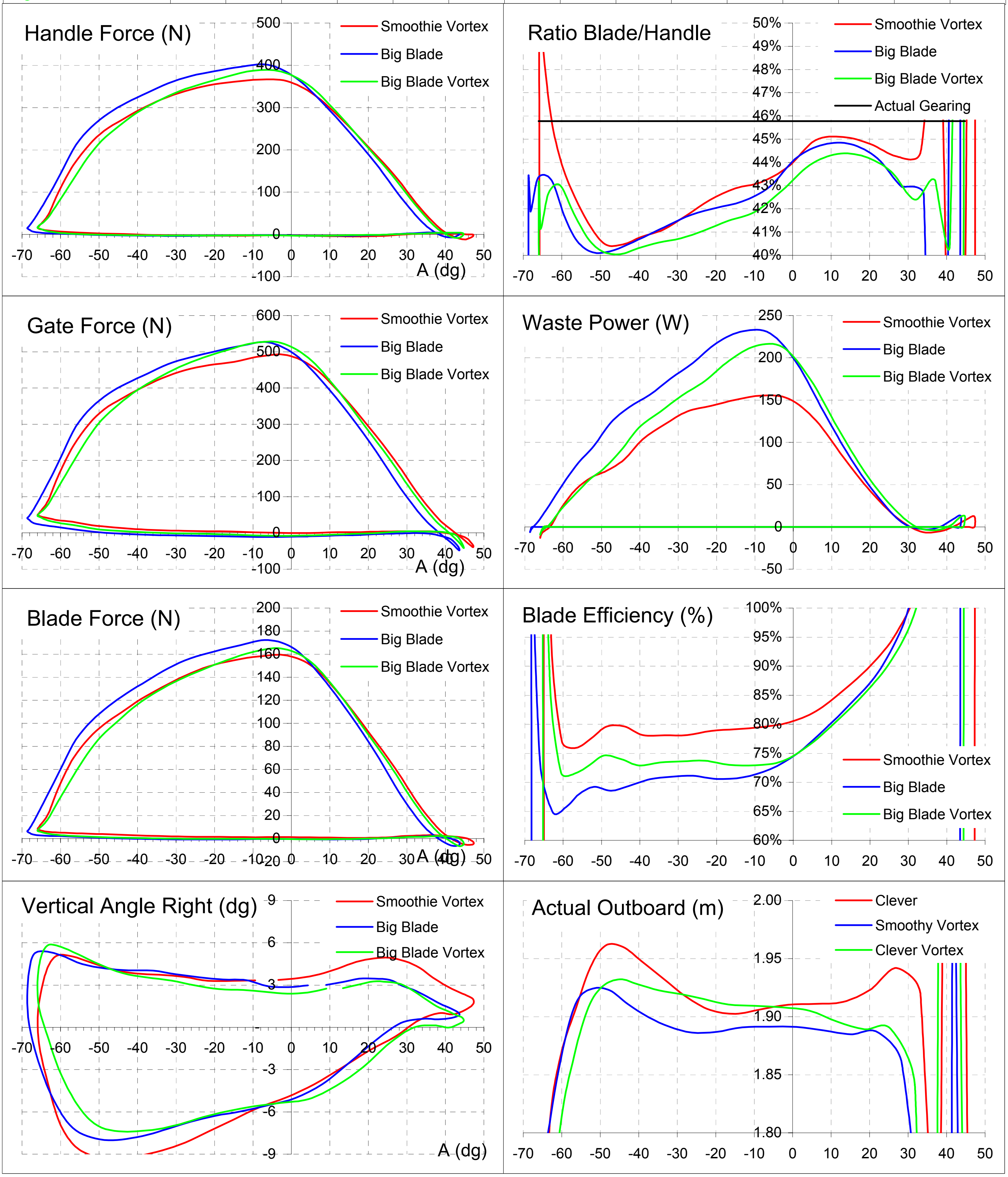
Big Blade	23.8	3.68	112.2	87.7%	1.37	202.1	269.4	84.9	42.0%	220.3	42.8	73.6%	11.9	7.27	2.27
Big Blade Vortex	23.9	3.79	110.7	89.2%	1.37	186.5	258.7	77.8	41.7%	208.8	36.5	76.1%	11.6	6.41	2.03



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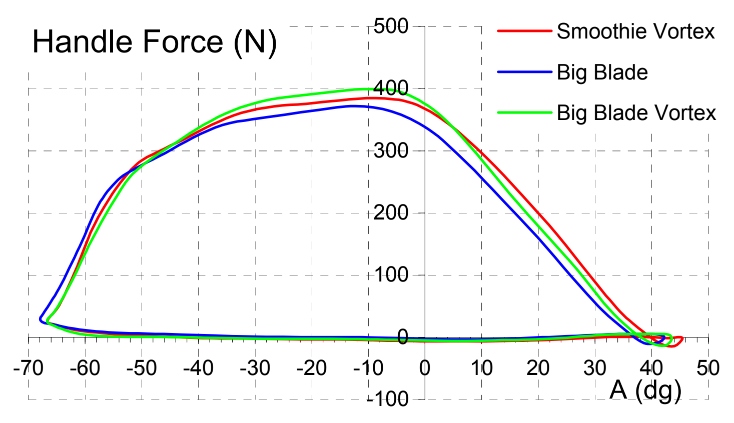

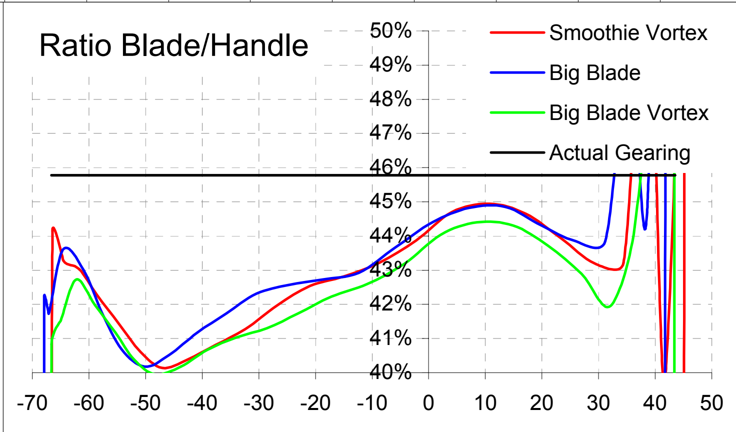

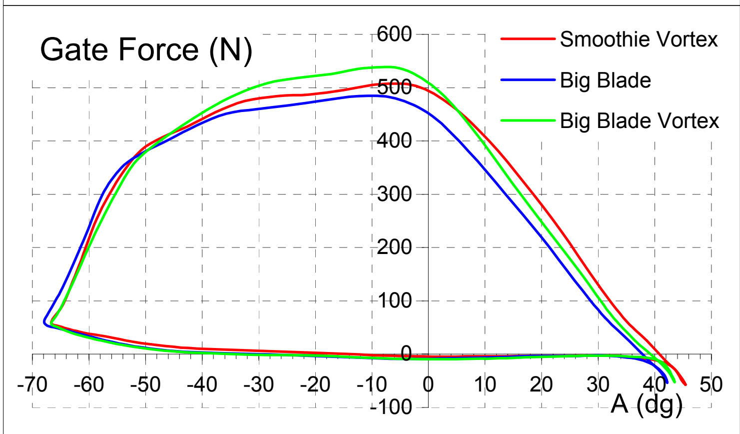

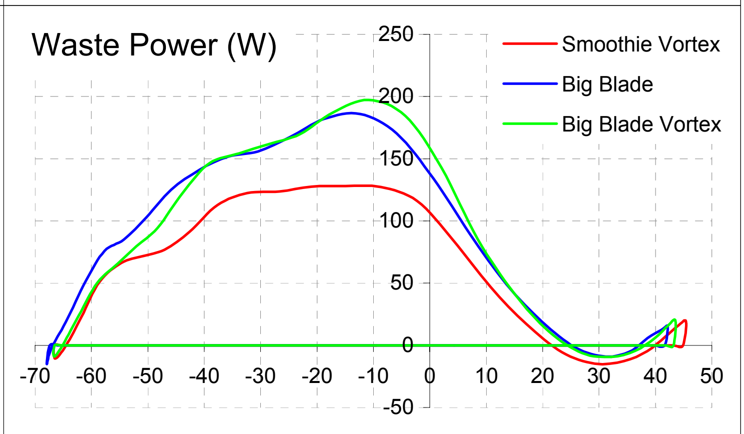

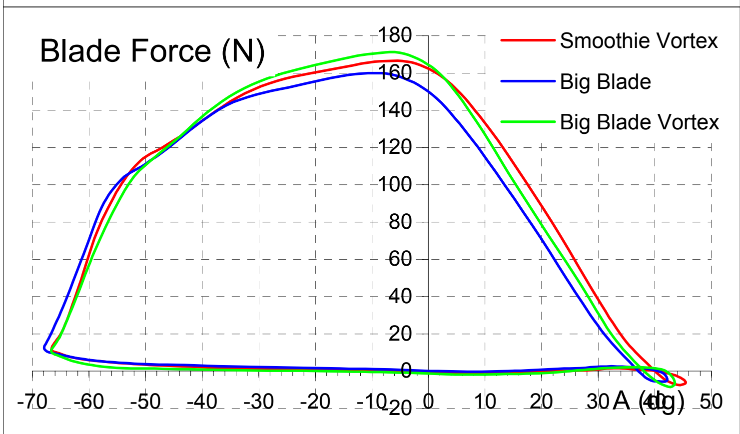

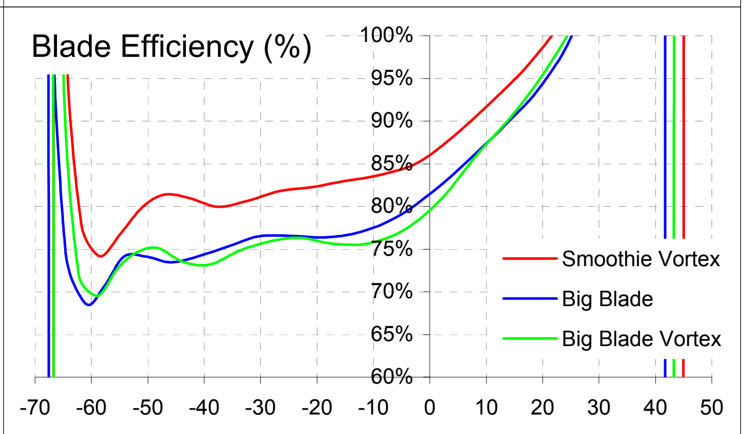

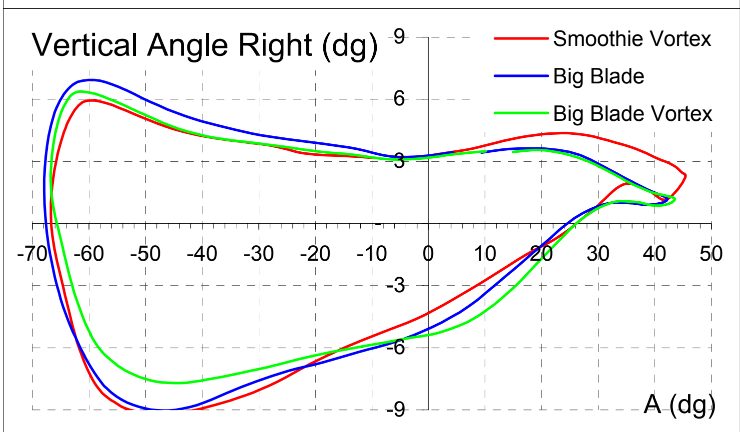

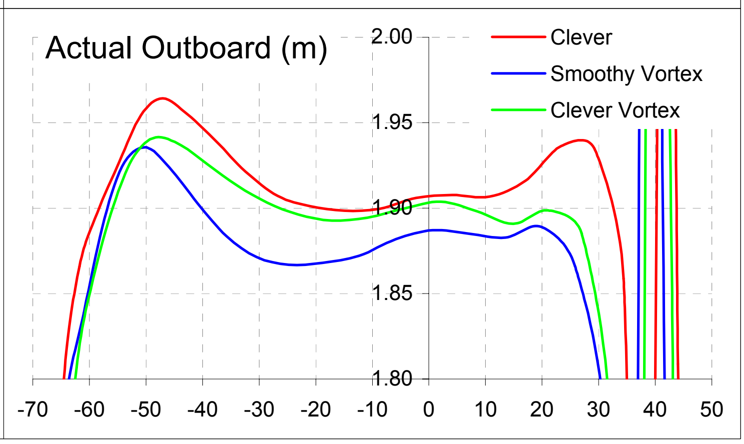

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Smoothie Vortex	31.2	4.55	108.9	81.8%	1.60	218.1	290.5	92.0	42.2%	278.3	44.3	79.4%	0.3	4.64	1.72
Big Blade	31.1	4.63	107.8	85.6%	1.60	226.0	300.5	96.9	42.9%	277.8	41.9	80.5%	11.3	3.47	1.67
Big Blade Vortex	31.4	4.62	108.8	83.8%	1.62	226.1	305.0	94.7	41.9%	298.4	47.3	79.2%	11.4	5.09	1.75