

Report No. 2984**Date : December 2025****Compiled By : MG****Lloyd's Register Foundation****Wind Propulsion Load Cell Feasibility Study****1 INTRODUCTION**

This feasibility study explores the development of a 4-legged contraflexure beam load cell for wind propulsion devices on ships. Due to limited access to reliable performance data, ship operators are hesitant to adopt zero-emission wind propulsion systems. A load cell would provide essential metrics to demonstrate fuel savings, assist with thrust optimisation, and enhance crew safety by enabling direct force monitoring. Real-time data will help prevent dangerous operating conditions, ensuring that wind propulsion systems are used safely and effectively. The study will include a design constraint analysis, followed by parametric design and finite element analysis to develop or understand load cell limitations.

Some of the values used in this project have been derived as typical values provided by technology providers. These values are not necessarily applicable to all devices but in general have been selected to be conservative.

2 DESIGN CONSTRAINT ANALYSIS**2.1 Geometric**

For the load cell to be adopted widely, it needs to be technology and ship agnostic. The obvious location for the cell is attached to the slew ring of the wind assist technology. Smart Green Shipping, a UK based wind assist technology developer, has provided some information about the typical size of slew rings. The rings vary in size depending on the side of the installed rig but for the purpose of this feasibility study a diameter of 2m will be assumed. Therefore, the load cell should also be of this scale so that it can be added to the existing base of rigs without major redesigns of their foundations.

An acceptable height of the load cell is assumed to be 5% of the overall height of the rig. Currently large rigs are reaching about 40m tall. Therefore, the height of the load cell should be limited to 2m.

2.2 Structural Design

The loads can be split into various categories:

- Aerodynamic loads
- Inertial loads due to the movement of the ship
- Gyroscopic loads (for Flettner rotor designs)

Static, dynamic and fatigue loads need to be considered.

Inertial Loads: Latest SGS rigs are 34m high and weigh around 30 tonnes. Several conservative assumptions have been made to estimate a maximum inertial load acting at the centre of mass of the rig. These are listed below:

VCG of Rig	32m
Roll Period	20s
Acceleration at extreme of motion	1.07 m/s ²
Force needed for this acceleration	32kN
Moment induced	0.864MNm

Gyroscopic loads have been calculated with data from Norse Power (Norse Power, n.d.). The weight and moment of inertia of the rotor have not been given, so estimates have been used. The rotor is built of composites so is likely to be relatively lightweight with most of the weight of the structure in the mast beneath the rotating element.

Rotor Speed	0-180 rpm (0-19 rad/s)
Rotor sail assembly weight	63t (for largest rig)
Foundation weight	24t
Max Continuous thrust	350kN
Rotor Diameter	5m
Rotor Height	35m
Rotor Weight	10t (estimate)
Rotor Moment of inertia	250000kg m ²

Assuming that the vessel is rolling with a roll period of 20s and an amplitude of 3 degrees the procession angular velocity is 0.02 rad/s. The angular velocity of the rotor 19rad/s. Using the gyroscopic torque equation:

$$T = I\omega\omega_p$$

The torque needed to process the rotor at this angular velocity is 20kNm. As this moment is two orders of magnitude smaller than the moments generated by the aerodynamic forces, the gyroscopic forces will be neglected from the rest of the calculations.

The inertial loads and gyroscopic loads will not be in phase as the inertial loads will be largest at the extremes of the roll motion and the gyroscopic load will be maximum when the vessel passes through upright when the procession angular velocity is at its maximum.

2.3 Deflection Limits

To accurately measure the loads, sufficient deflection of the dynamometer is needed for the sensors to make measurements. However, this deflection should not be so much as to change the geometry of the system significantly or reduce the stiffness such that large amplitude oscillations occur. Fatigue limits must be considered if the load cell is to be in service for a significant period of time.

Strain Gauge Limits: HITEC Sensors – a company with provides custom load cell and instrumentation – was able to provide some guidance about the performance of the latest strain gauge technology (Domenic El-Achkar, 2025): The latest semiconductor strain gauges are sensitive to temperature and therefore are perhaps not appropriate for a maritime (non-laboratory) applications. Using the equation for a full Wheatstone bridge with two gauges in tension and two in compression then the equation for the output voltage is:

$$V_{out} = V_{ex}(GF \epsilon)$$

If we assume a typical data acquisition system with a ±10V range and 24 bit resolution this provides a resolution of ~1 μV and therefore with a gauge factor of two and an excitation voltage of 5V we can resolve down to 0.1 με.

The yield strain of mild steel is ~2000 με. A full range measurement of 100 με would provide a sufficient resolution while maintaining the stiffness of the structure.

Linear Variable Differential Transformer (LVDT) limits: A load cell can be constructed so that the displacement of the live side of the load cell is used instead of measuring strains on the surface of the flexures. In this case an LVDT is used. The resolution of these devices can be down to around 0.6 μm. A full scale

deflection of 100 μm would provide a reasonable level of precision in the measurement. The Wolfson Unit currently uses LVDT sensors in their model scale force blocks as shown in figure 1.

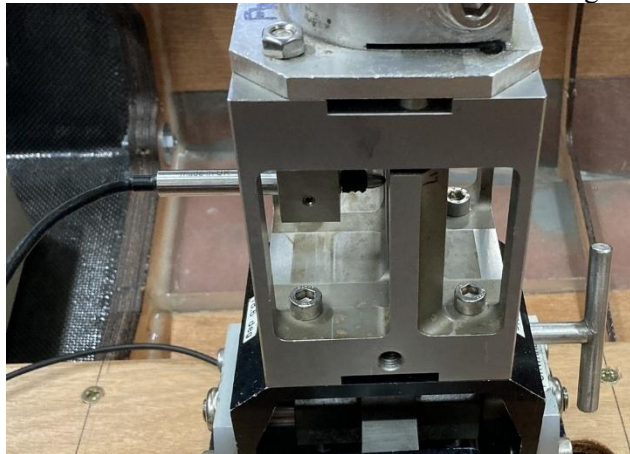


Figure 1 Model Scale Four-Leg Contraflexure Beam Load Cell with LVDT.

2.4 Operational Limits

Although the structural limits of the rigs provides an absolute limit, wind statistics data can provide a more realistic operational range. The load cell should be operational for a high percentage of the conditions which ships would experience at sea. Using the Global Wind Probability Matrix from the (IMO, 2021) it can be seen that 95% of voyages of ships are below 25kn of wind. Therefore, 25kn will be used to derive the maximum aerodynamic forces of a typical rig.

The maximum values of thrust and sideforce have been selected for 25kn of wind speed and a ship speed of 13kn. These values are used as the maximum normal operating conditions and therefore should be the full range of the load cell measurement. The Wolfson Unit has produced performance polars for various wind assist technologies and therefore is able to draw on this data to provide realistic values of thrust and sideforce for these sailing conditions.

These are the example loads which will be used in the FEA analysis to size the flexures to aim to achieve the LVDT displacement limit between the top and bottom plate. Inertial loads have been added to this to provide a maximum value. Gyroscopic loads have not been included as these are in antiphase with the inertial loads and therefore would be negligible at the extremes of the rolling motion. The inertial loads have been added to the sideforce value as it has been assumed that roll motions will be significantly more energetic than pitch motions.

Limit	Value
Drive force	100kN (10t)
Sideforce	177kN (18t)
Self Weight	294kN (30t)
Min full range displacement LVDT	100 μm
Min full range strain	100 $\mu\epsilon$

2.5 Classification and Insurance

The load cell must meet the standards of the classification societies if the vessel is to be insured. In 2025 Lloyds Register released a Guidance Note (Lloyd's Register, 2025) on wind assisted propulsion systems. Included in this document is details of structural assessment required. This includes safety factor levels for normal operation and survival at sea. An allowance can be applied if detailed FEA analysis is completed. Assuming a yield stress of 240MPa for mild steel the below table provides the values of allowable stress:

Loading Condition	Allowable First Principle Stress	Allowable Von Mises Stress
Normal Operation at Sea	140MPa	154MPa
Survival at Sea	180MPa	197MPa

3 EVALUATION OF DESIGNS

Although this study will focus on the four-legged contraflexure beam load cell, a number of different designs were also considered.

3.1 Off-the-Shelf Load Cells

Existing technology for load measurement was investigated. Generally, it was found that only 6 degree of freedom devices were designed to carry large moments. Devices which measured in fewer degrees of freedom are designed to do so without the presence of large forces and moments in their unmeasured axes. This limited the search to 6 axis devices.

Typical values for a high force 6 axis cell are listed in the table below:

Axis	Measurement Range
F_x & F_y	20kN
F_z	100kN
M_x & M_y	2kNm
M_z	1.5kNm

Table 1 Off the shelf load cell measurement range.

These devices fall far short of the full-scale moment range needed for this application. The moment carried by each individual cell could be reduced by using multiple cells with a large separation. If 8 devices were spaced evenly around a ring at the base of the rig, the diameter of the ring would need to be >100m, significantly larger than the beam of ships. It is clear from this thought experiment that a bespoke system is needed.

3.2 Pyramidal Structure

Wind tunnel engineers are familiar with the problem of measuring forces remotely. Wind tunnel force measurement equipment cannot be inside the wind tunnel and therefore affect the flow. One method of mitigating this is to use a pyramidal balance. The design of the balance allows the engineers to resolve the moments around a virtual centre.

A pyramidal arrangement of struts creates a structure which, if it is loaded at the virtual centre, creates forces of pure tension and compression in the struts that make it up. However, if the line of action of the force is not through the virtual centre, then an additional reaction moment is provided by the balance and this can be measured. Figure X from (Hufnagel, 2022) shows the basic layout of a pyramidal balance.

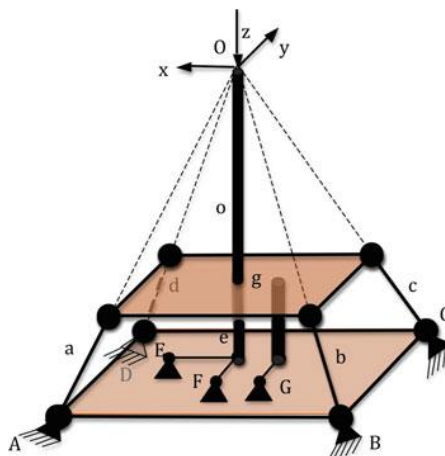


Figure 2 Pyramidal Balance

Uniaxial load cells are less complex to design and can be more easily found in the force ranges needed for this application. However, due to the relatively high centre of pressure of the device and the relatively small footprint of foundation, the angle at which the struts would be placed would be very shallow and would

therefore be very sensitive to forces acting at a distance from the virtual centre. It is likely that the centre of effort of the aerodynamic forces will not change drastically during operation. However, the inertial loads may not be co-located with this point.

3.3 Thin Walled Ring

Most wind assist designs are mounted on a “slew ring” at their base to allow them to be yawed to adopt the best attitude to the wind. An array of strain gauges over an annular ring could be used to measure the strain field over the ring. Assuming that the out-of-plane stresses were small, because the ring is thin walled, would allow for the loading condition to be calculated. However, the strains caused by the bending moment will be an order of magnitude larger than the drive/sideforce strains. Therefore, it is difficult to determine if this method would be possible with real world signals which contain noise and anomalies.

3.4 Shear Beam Design

A shear beam load cell measures the shear strain in the webbing of an “I” shaped beam. Because it directly measures the shear (rather than bending moment) it is a good design for rejecting bending moment. This is a promising alternative design to the contraflexure beam design.

3.5 4 Legged Contraflexure Beam Design

This report will consider this design in depth with an FEA parametric study. This design is stiff in all directions except the axis they are measuring. They have good moment rejection but are susceptible to buckling if a large force is applied parallel to the flexures.

4 FEA ANALYSIS & PARAMETRIC STUDY

A parametric study was conducted on a 4-legged contraflexure beam design. The geometry of the flexures was varied while the loading conditions remained the same and the performance function was calculated for each design to select the best configuration. 11 configurations were simulated. Each load cell was tested with drive force only and with drive force and side force applied. This allowed the magnitude of cross talk between the axes to be evaluated. Displacement of the top plate relative to the bottom plate was measured in all three axes as well as angular deflection of the top plate. The deflection can then be compared to the resolution of LVDT displacement sensors.

For each FEA analysis a local mesh refinement was completed and convergence reached.

4.1 Comparison Between Designs

The same loading condition is applied to each design and the geometry was altered until the desired deflection limit was reached. A performance function was used to compare between designs:

$$P = \frac{SF_{min} \times D}{CT_e \times \alpha}$$

Where:

SF_{min} = Minimum Von Mises Stress Safety Factor

D = Deflection of live plate relative to grounded plate in direction of interest.

CT_e = Cross talk error

This is the normalised error in the deflection value between FEA run for forces only in the drive force direction and with sideforce applied as well.

α = Angular displacement of the top of force block

Parameters were varied until the design constraints were met. The results of the final design are presented in the table below:

Variables	Loading Condition		Design Constraints
	Drive Force and Side Force	Drive force	
Max Principal stress - MPa	117.50	40.97	<140
Max Von Mises Stress - MPa	111.10	0.02	<154
Angle of top plate - deg	0.01	0.00	
Drive Direction Displacement - μm	215.60	212.50	>100
Side Force Direction Displacement - μm	133.40	8.60	
Cross Talk - %	1.46		

Cross talk is defined as the percentage error in the drive direction displacement in the presence of the side force. This error could be removed with an interaction matrix. However, a small value of cross talk shows that the load cell is insensitive to off axis loads.

This design has been optimised to measure the force in one direction by reducing the stiffness in that direction while maintaining it in the other directions. Therefore, if it were desired to measure both drive force and side force it would be necessary to stack two load cells oriented orthogonally. This would add to the stack height of the load cell but with leg lengths of 0.5m this is still well below the 2m limit outlined in the design constraints section.

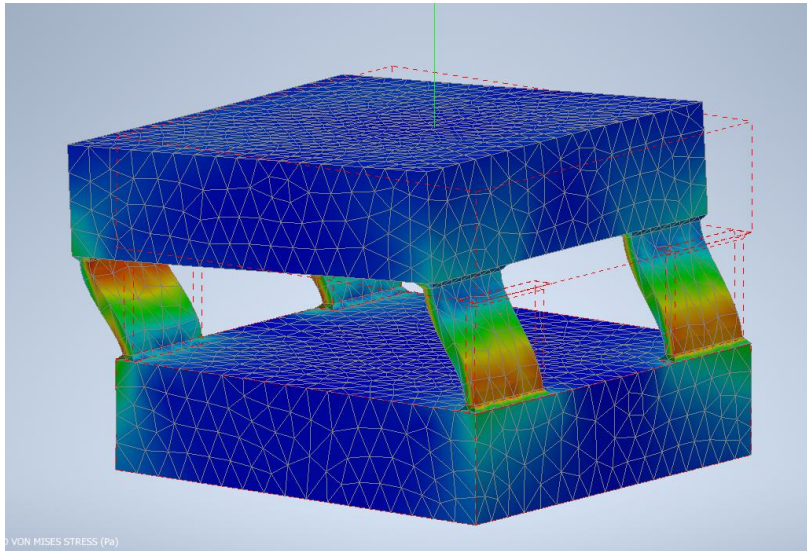


Figure 3 Amplified Displacement Plot of Result of Parametric Study

5 CONCLUSION

- This feasibility study has provided the design constraints needed to design a load cell for the wind assisted shipping industry. Considering various factors including geometric, operational, instrumentation and classification approval.
- Several load cell designs were compared. It was found that rejection of the large bending moment presented a challenge in practical terms. A parametric study of a four-legged contraflexure beam design was completed.
- A performance function was created to compare different designs.
- A final geometry was produced which met the design constraints set in the first section of the report.

6 FUTURE WORK

The next phase of this study will aim to secure funding to build a scale prototype of the load cell and load it physically in a heavy structures laboratory. This phase of the study will allow for the interactive effects to be

quantified particularly the extent to which the effect of bending moment can be removed from the measurement of the side and drive forces. This phase of the design would consider the practicalities of mounting the load cell to the ship and the wind assist technologies as well as overload protection.

7 REFERENCES

- Domenic El-Achkar. (2025). *Email exchange*. HiTec Sensors.
- Hufnagel, K. (2022). *Wind Tunnel Balances*. Springer Nature Switzerland AG.
- IMO. (2021). *2021 GUIDANCE ON TREATMENT OF INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES FOR CALCULATION AND VERIFICATION OF THE ATTAINED EEDI AND EEXI*.
- Lloyd's Register. (2025). LR-GN-044 Guidance Notes on Wind Assisted Propulsion Systems.
- Norse Power. (n.d.). Retrieved from https://www.norsepower.com/app/uploads/2023/08/brochure_ENG_screen.pdf