SuperBASS Tripod for Benthic Turbulence Measurement

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ABSTRACT: - Seafloor flow induced processes are generally studied from rigid structures. Where undisturbed flow is important, open structures are used, tripods being the choice for omnidirectional flow. Stiffness as well as openness is important to delay excitation of vibrations that can contaminate velocity measurements, masking turbulence in the flow. SuperBASS, measuring velocity and turbulence at seven heights from 0.3 to 7 m above bottom, is 8 m tall, 4 m between footpads, weighs 530 kg, and is stable to overturning to 1 m/s flow velocity. A "Y" channel of rectangular cross section from the bottom of the legs supports the base of the acoustic current meter array, eliminating the need for stiffener struts on the faces of the tripod. While this design reduces turbulence at all sensor heights that would have come from the wake of upstream stiffening struts, a mean upward component of flow is observed on the lower sensors from separation of the flow over the "Y" channel near the seabed.

I. INTRODUCTION

Flow from currents, and even waves, is predominantly horizontal near the seabed. Turbulent eddies however contain velocity fluctuations in three dimensions. BASS [1,2] measures 3-D velocity over a 15 cm diameter with a differential acoustic travel-time technique [3]. Sensor cages are stacked into a vertical tower to measure velocity and turbulent fluctuations across the benthic boundary layer for comparison to wall bounded flow models and to estimate benthic shear stress for sediment transport and mixing studies. Where the flow may come from any direction, tripods support the BASS sensor tower. In rivers or off beaches where the flow direction is constrained by a lateral boundary, quadrapods are used to eliminate the upstream leg and the quadrapod is aligned with the flow. But in all cases, a stiff structure is required. In 1996, a larger than usual tripod was constructed to measure turbulence in the Coastal Mixing and Optics Experiment. Openness and stiffness were stressed in this design to obtain the lowest noise floor practical for a benthic turbulence and mixing study.

II. TRIPOD STRUCTURE

The simplest stable space frame that will sit on the seafloor is a tetrahedron. If the seafloor can resist lateral forces as well as downward forces, the horizontal members between legs are not absolutely required and the tripod can have as few as three major struts, coming to a vertex at the top. This primitive structure has four pinned vertices and, since the bottom fixes the lower three, the top vertex is fixed in all three dimensions.

The primitive tripod cannot carry any payload except that which can be hung from the top vertex. The struts cannot carry any load transverse to their length without some distortion. The seemingly benign addition of a platform attached to the mid-span of the three legs, while adding useful space for instruments, permits substantial loads to be applied transverse to the legs and takes the stiffness out of the structure. The solution is to add a diagonal strut from each attachment point of the platform to another vertex. This reestablishes a pinned structure in which loads are not imposed on the struts except along their axes. But the three strut structure has become nine struts: the three legs, three edges of the platform, and the three diagonal stiffeners.

A tripod with intermediate platform for instrument cases is satisfactory for simple applications and we have used this for lightly loaded instruments. But if the footpads are heavy to prevent overturning of the tripod in strong currents, additional struts may be needed for the time when the tripod is hanging from a crane. The simplest solution is to connect the feet with struts, increasing the number of elements from 9 to 12. These last struts are not necessary when the tripod is on the bottom when the seafloor serves to fix the footpads. The struts between the feet are serious disturbers of the near bottom flow and are undesirable if one is interested in very near bottom flow. A solution that we have employed in these cases is to extend struts from the feet to two corners of the intermediate platform in addition to the original leg from the foot to the vertex of the tripod. This creates a cross of struts in the face beneath the platform and we have generally joined the struts where they cross to shorten the span, stiffening the struts. The structure of the tripod begins to look like a truss with multiple triangles in the faces. The bottom is relatively uncluttered but the cost is more structure at various heights above the bottom.

As a rule of thumb, we avoid measurements of flow, especially turbulent flow, within two diameters, vertically, of the flow disturber. For example, instrument cases on a platform occupy 25 cm of height. If the platform is at 3.5 meters above bottom, no flow measurements are made between 3.0 mab and 4.25 mab. A crossing of struts creates a disturbance of about 10 cm and if it is at a height of 1.5 mab, it prevents measurements between 1.3 mab and 1.7 mab.

The tradeoff in tripod design is between stiffness and wake. Adding struts increases stiffness and in most cases returns a compromised structure subject to bending loads to a pure pinned joint truss structure. As the projected area of the tripod with struts increases, wake effects become larger. But wake is not the only concern with struts; flow interacts with these struts to cause vibrations. A stationary strut leaves a wake. But the shedding of vortices by the strut may cause the strut to vibrate and a vibrating strut has a drag coefficient many times that of a

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stationary strut. Strouhal vibrations [4] increase the drag force, add structure to the wake, and transmit vibrations to the payload on the tripod. Fig. 1 illustrates typical tripods used in benthic flow studies. The elements are added in response to need for stiffness.

III. Oscillations

Two kinds of oscillations are observed on struts in a flow: transverse and streamwise. While the frequency of transverse oscillations are predicted by Strouhal as

$$f_s = 0.2 \cdot v/d$$

where v is the velocity transverse to the strut and d is the diameter of the strut, the frequency of oscillations in the direction of the flow is twice that. A typical shelf flow of 30 cm/s and a strut diameter of 5 cm gives a Strouhal frequency of 1.2 Hz (or 2.4 Hz in the direction of the flow).

Large amplitude oscillations occur when the natural bending frequency of the strut coincides with the Strouhal excitation frequency. Aluminum struts in the tripods we use vary typically from 3 Hz to 5 Hz for their fundamental mode of oscillation so they are not always excited strongly by the flow and even then are likely to oscillate in the streamwise direction rather than transversely. A short tripod designed for benthic vorticity measurements in strong flow [5] was deployed in a coastal channel and visited by divers during peak tidal current. With current at the surface of 150 cm/s and about 80 cm/s at 1 meter above bottom, only one strut was observed to oscillate and it was in the streamwise direction. This strut was a cross brace of smaller diameter, 3.6 cm, and greater length than the main strut since it went between a vertex on the intermediate platform and a lower corner. Thus, it had a lower fundamental bending frequency than the main struts but a higher Strouhal frequency than the larger diameter struts. Yet even it wasn't excited in the lower frequency transverse mode. This illustrates the good news that Strouhal oscillations of larger diameter struts may be too low for even their lowest natural frequency for moderately strong flows. At greater flow velocity the streamwise fundamental oscillation may be excited. As the Strouhal frequency increases due to higher velocity, it may be desirable to raise the natural frequency of the strut by increasing Young's modulus as by switching from aluminum to steel.

Cables are also used for cross braces since they are thinner and cast a smaller wake. They have a higher Strouhal frequency from their smaller diameter but a lower natural frequency of oscillation since they derive their restoring force from tension rather than stiffness. With the low tensions possible on large open tripods, the frequency of the fundamental transverse wave on the wire may be below 5 Hz. This falls within the Strouhal oscillation for moderate currents. However, even with this overlap, things are not as bad as they might be because the cables are relatively small and because they do not behave coherently over their entire length. The cables are very many diameters long, typically more than 200 diameters, and do not shed vortices coherently over that length. Divers have not observed cables in strong currents to detect strumming nor have

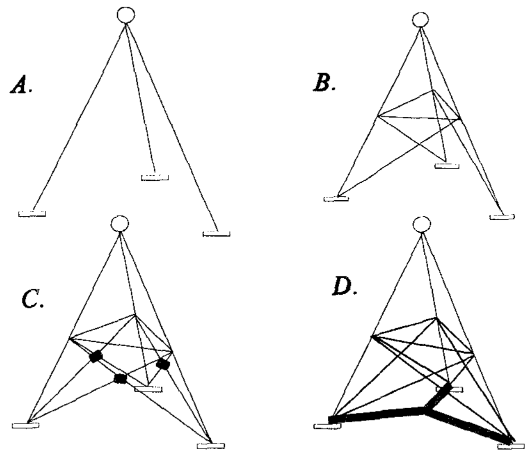

Fig. 1. A. Primitive tripod with feet fixed by seafloor. B. Tripod with platform attached to the struts at an intermediate position. Diagonal stiffening struts are required to regain stiffness of the tripod. C. Crossed stiffening struts to position feet during handling, before making contact with the seafloor. Intersection of the diagonal stiffeners blocks flow. D. Cable stiffened face of open tripod for minimum flow obstruction with "Y" box channel to position feet during handling.

accelerometers been employed to monitor vibrations at narrow bands, but velocity sampled at 160 ms intervals in 10 minute bursts on a tripod in strong current has not revealed spectral peaks uncorrelated with waves. This indicates that Strouhal excited vibrations are not significant below 3 Hz.

Generally, the bottoms of tripods have been free of struts, that is they have depended on diagonal braces from the feet to an intermediate level to hold the feet during handling. On several tripods however, it was necessary to keep the face free of cross braces and a strut between feet was necessary for handling if not on the bottom. To avoid unduly tripping the bottom boundary layer before it was measured, the struts connecting the feet were brought to the center of the tripod, where the measurement tower was located. This avoided upstream, near bottom obstructions, but it produced a potential flow artifact at the measurement location from the effective change in topography. Had the strut been flush with the bottom, this effect would have vanished. The strut was elevated above bottom to avoid being bent by bottom contact and it was thick to prevent buckling so it had potential flow both from its own thickness and from its image on the other side of the boundary. With a thickness of 5 cm extending from 10 cm to 15 cm above the bottom, the strut looks like a pair of channels 25 cm apart. 15 cm above the top of the strut (30 cm above the bottom) the distortion due to the strut is an acceleration of 2.5/17.5 + 2.5/42.5 in the streamwise direction, a 20% effect. The change in direction in the horizontal plane is not major nor is the velocity increase over the unobstructed velocity very important. What is noticeable is an asymmetry in the flow over the strut.

The strut is a rectangular channel 5 cm thick by 15 cm wide. The shape is not streamlined but the bluff entrance shape is not significant to the problem. The bluff exit shape is more serious. Flow separation at the exit shape produces an asymmetry that results in an upward component of flow at the sensors no matter which direction the flow is going. Empirically, this seems to be a few percent of the horizontal velocity. Fig. 2 shows the geometry and the streamlines.

IV. Stability

A fundamental task of a bottom tripod is to remain upright while exposed to current and waves. Initial stability is generally sufficient to insure the tripod does not fall over since when a foot lifts from the bottom, stability always decreases and only decrease in flow velocity can save the tripod from falling. Actually, wave flow superimposed on mean current is the instantaneous velocity that can cause a foot to lift and the wave may well reverse its direction before the tripod falls so the response time of a large tripod may provide some margin of safety.

Projected area of struts and instruments to the flow with a suitable drag coefficient and the velocity squared at the obstructing height create the force distribution on the tripod. The overturning moment is the height times the element of force integrated over the total height of the tripod.

$$M_o = C_D \frac{\rho}{2} \int z v^2(z)\, x(z)\, dz$$

M_o is the overturning moment, C_D is the drag coefficient, assumed to be 1.4 for bluff bodies, ρ is the density of seawater, $v(z)$ is the velocity at height z, $x(z)$ is the projected horizontal element of area at the height z. It is conservative to include elements of the structure blocked by those upstream if the separation between them is more than the diameter of the upstream element. When objects are packed densely, as they are on the intermediate platform on most of our tripods, the span of the platform at height z is appropriate.

The restoring moment is simply the weight in water of the tripod times the distance from the center of mass to the line connecting the feet about which the tripod might rotate. The center of mass must be projected downward to a horizontal plane containing the feet about which rotation might occur to get the offset distance. This takes account of a tripod on a sloping bottom. Once the maximum instantaneous current that might be expected is specified, only the weight and the spacing of the feet are easily adjustable.

SuperBASS was designed to extend through the mixed bottom boundary layer on the continental shelf off the coast of New England for turbulence observations in the Coastal Mixing and Optics experiment. It was designed to be 8 meters tall with velocity sensors from 0.3 to 7 mab. Since turbulence was to be measured at each height but especially at the 0.3 m height, all the concerns about flow disturbance and vibrations were present in addition to the concern about overturning. In a sense, all that we had learned about tripods was needed in the design of SuperBASS.

Drag was minimized first to provide the most windows to measure undisturbed flow and second to minimize overturning

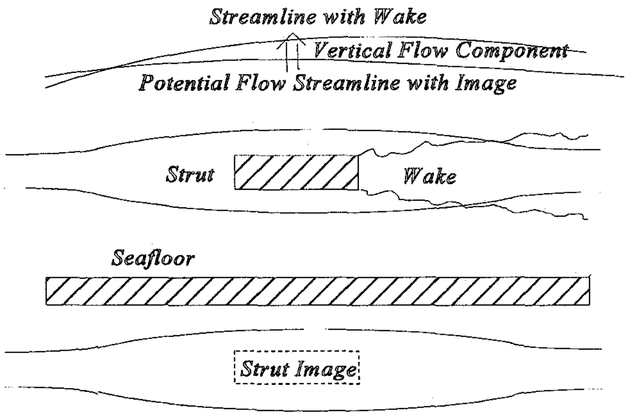

Fig. 2. The rectangular strut separating feet produces potential flow distortion accelerating the streamwise velocity but also producing a vertical component of velocity for any flow direction. The bottom distorts the flow as well, represented in the figure as an image below the seafloor.

moment. The overturning moment in 1 m/s flow for SuperBASS was calculated to be 8400 nt m (6300 ft lb). Aluminum 5 cm tubes were used for the upper section of the tripod, above the instrument case platform. Stainless steel 5 cm tubes were used for the longer struts below the instrument case platform. The greater weight of stainless was desirable to increase the threshold for overturning but the selection of steel over aluminum was to raise the frequency of the strut in bending. The higher Young's modulus of steel over aluminum raised the fundamental resonance frequency to 5 Hz over the 3 Hz of aluminum. (It should be noted that this is the fundamental resonant frequency in air. Water filling the tube and the added mass effect of a cylinder vibrating transversely in water lowers this from 5 Hz to 4 Hz.) No tubular cross braces were used in the lower section of the tripod to minimize wake generation, crossed guy wires serving to stiffen the face instead. These wires had a fundamental frequency of vibration of 5 Hz in air (4 Hz in water). Finally, stainless rectangular channel was used in a "Y" shape to hold the feet in fixed relation to one another. The feet were 38 cm square blocks, 10 cm thick with 38 by 150 cm mild steel plate 1 cm thick bolted beneath. The large area both reduced the bearing load on the expected mud bottom and moved the rotation line for overturning outboard to 2 m from the center of mass. Total tripod wet weight including feet was 520 kg so the moment required to lift a foot was 10,200 nt m, above the overturning moment in 1 m/s flow.

It was felt after the first recovery that the suction of the large feet on the cohesive bottom was excessive (the first lift line broke during recovery attempts) and two large rectangular holes were cut in each foot to reduce the surface area without moving the offset radius for overturning.

Recovery of shallow water tripods is by lift line so nothing is left behind to foul fishing nets. To minimize the drag of the packed recovery lift line, messenger floats were used with light line to subsequently pull the heavier lift line from baskets [6]. This permitted quadruply redundant lift lines in a vertical slab only 35 cm high. While densely packed, the intermediate platform only denied flow measurements from 3.2 to 4.9 mab. The SuperBASS tripod is shown in Fig. 3.

V. MATERIALS

Stainless steel was used for most of the tripod and it was protected from crevice corrosion and general wastage by the 400 kg of mild steel feet. The upper part of the tripod was aluminum tubing and this was electrically isolated from the bottom stainless part with Delrin sleeves and washers. The aluminum (6061-T6) was protected with zinc anodes. Instrument cases were anodized aluminum and these were secured to fiberglass grating at the instrument platform with stainless steel hose-clamps but the hose-clamps were separated from any metal - aluminum, anodized aluminum, stainless steel, mild steel, or zinc - with neoprene strips.

Guys to support the stainless steel flowmeter tower in the center of the tripod were thin stainless wire. This wire was vulnerable and was thus protected by mild steel turnbuckles. The entire turnbuckle-guy assembly was isolated at each end with Delrin sleeves and rubber strips. Despite this, the guys were generally broken upon 90 day turnaround - mostly through dissolution of the turnbuckles. Sensors were similarly isolated from other metal parts of the tripod. But the need for this was brought home when on one turnaround, an aluminum conductivity sensor was largely consumed through touching the end of a cotter pin through a stainless turnbuckle on the crossbrace wires. Loss of tower guys caused deflection of electrical cables with change in calibration of the BASS acoustic flow sensors so it was more than inconvenient to have corrosion of critical components.

On one recovery, we bent an aluminum upper tripod strut which cracked causing loss of the upper flowmeter tower. The aluminum struts were then replaced with stainless which is more ductile than aluminum. Weight, even weight high on the tripod, increases initial stability of the tripod to overturning. And the higher frequency of oscillation retards onset of vibration for steel over aluminum.

Consumption of the mild steel feet, of which there is an abundant supply, illustrates the effect of a large surface area of stainless steel on corrosion current. The zinc anodes on the painted aluminum tubing were also consumed but at a small fraction of the mass of the mild steel, due to the corrosion current being limited to by the small exposed area of bare aluminum.

VI. CONCLUSIONS

Benthic tripods must be stiff and if they are to measure flow they must also be open and free of wake distortion where the flow is measured. Strouhal oscillation in the wake may excite bending oscillations of the struts that can vibrate the sensors and increase the drag and thus the wake. Minimizing projected area decreases susceptibility to overturning while maximizing the region where flow can be measured. Stiffness requires pinned joints and truss structure without loads on mid-spans of struts. Weight and spread of feet is the most effective way to prevent overturning. Open faces of the tripod may require struts between the feet to permit handling the tripod when it is not resting on the seafloor but these may create potential flow acceleration near the bottom and by flow separation, may create upward flow over the struts for all flow directions.

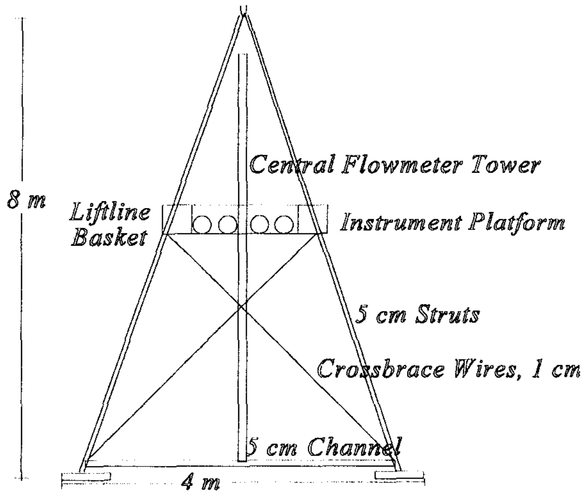

Fig. 3. SuperBASS tripod supports a tower of acoustic current meters (BASS) from 30 cm above bottom to 7 meters above bottom. To minimize turbulent wakes at the sensing levels, the faces are open, stiffened with crossbrace wires. The feet are held (as well as the bottom of the BASS tower) by a "Y" channel

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