Flip: An Oceanographic Buoy

A novel structure provides a quiet platform of great stability for acoustic and other research at sea.

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The study of sound in the ocean has long had military importance and is becoming increasingly recognized as a part of physical oceanography, of scientific interest in its own right, and as a versatile element of technique, useful, for example, in measuring depths, following the movements of organisms or internal waves, locating experimental objects, communicating information, probing the earth's crust below the sea bottom, and in many other ways.

Acoustic Platforms

In any typical acoustic investigation, receiving hydrophones are needed. These must be, within some tolerance, quiet, this is to say, free of sound generated as a result of the presence of the hydrophone itself, or of related structures. When reception of very low level sound, or very precise measurement, is needed, flow of water past the hydrophone will be objectionable and is to be avoided in so far as possible.

Placing the instrument at the bottom of the ocean is often a desirable method, but is convenient only for locations relatively near shore, or in shallow water. It is technically possible to moor a buoy carrying a hydrophone at almost any place in the ocean, but in the deep areas such an installation tends to be elaborate, and the risk of flow-excited noise increases as longer lengths of cable are exposed to possible currents. Such technique has been little explored.

The more usual method of putting a hydrophone in an arbitrary place within the deep ocean is to suspend it from a ship. In this case, the wave-generated motions of the ship may create serious difficulty. A second source of ship motion is the wind. A drifting ship will be blown downwind at a velocity which is frequently troublesome, while the use of ship's propulsion to offset this velocity will usually be prohibitively noisy. In these circumstances, systems using slack cable and neutrally and positively buoyant bodies, or other means of mechanical isolation, are commonly used.

If the experiments are of a direction-finding nature, an array of hydrophones will be required. The positions of the individual hydrophones relative to one another must be fixed, and the orientation of the array as a whole, if not absolutely fixed, must be known from instant to instant. If this is accomplished by rigid attachment of the array to the ship, it must be particularly quiet and stable. A submarine may be the preferred platform, since it can hover at a depth below most wave action and is often well-organized for "silent" operation.

Staff members of the Marine Physical Laboratory of the Scripps Institution of Oceanography have been engaged in an investigation for which none of the three types of acoustic platform promised to be adequately adaptable. The problem was (and is) a precise study of the orientation and degree of perfection of acoustic wavefronts which are received from a source at a distant point after propagation over various long acoustic paths in the deep ocean. It was desired to compare accurately the direction of acoustic arrival with the direction of the source as judged optically or by other transmissions through the atmosphere. This requirement lay considerably beyond the capabilities of a submarine periscope; requirements on quietness and stability for the hydrophone array were equally beyond the possibilities for a conventional surface ship. This situation led to the planning, based on a principle long familiar to oceanographers and often used on a smaller scale, of the large manned spar buoy *Flip* (Floating Instrument Platform).

This platform has reasonable mobility, being towable in the horizontal position. When vertical it is an acoustically quiet platform of unprecedented stability extending simultaneously to 90 m below and 17 m above the sea surface. Once *Flip* was planned, it was evident that she would have important uses beyond the initial project, not only for instrumental investigations of the uppermost 90 m layer of the ocean, but as a more nearly stationary support from which to lower instruments by cable into the deeper layers. Not the least advantage is that of increased comfort and efficiency for seagoing scientists, for it should be quietly admitted that not all such are perfect sailors.

History of the Design

In 1960, F. N. Spiess and F. H. Fisher, respectively the director and a staff member of the Marine Physical Laboratory, proposed the design and construction of *Flip*. U.S. Navy funds were provided through the Office of Naval Research. M. Rosenblatt and Sons, and later L. R. Glosten and Associates, were consulted as naval architects.

The construction was carried out by Gunderson Brothers Engineering Company in Portland, Oregon. This firm does various other types of construction as well as shipbuilding, and the cylindrical hull structure of *Flip* clearly benefited from their experience in building tanks as well as ships. The buoy was launched 22 June 1962. Initial trials were carried out in Dabob Bay, near Seattle, with entirely satisfactory results. She was then towed to San Diego in September 1962. Since that time she has been in use by Scripps Institution.

Fisher and Spiess (*1*) have already discussed some of the considerations of design, described results of model tests, and presented measurements which are descriptive of the change of orienta-

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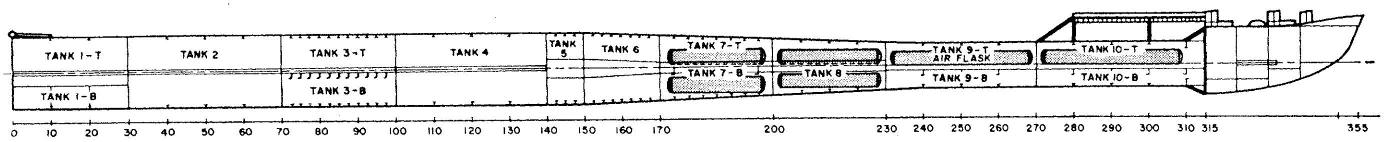


Fig. 1. *Flip*, vertical section showing compartmentation. Tanks 1B, 2, and 4 are free-flooding. Tank 1T is open to the sea at the bottom and can be vented or blown. Test pressure, 0.70 kg/cm^2. All other tanks withstand sea pressure; 5, 9T, 10T, and 10B are dry; 3T, 3B, 6, 7T, 7B, 8, and 9B are controlled buoyancy tanks.

tion, or flipping process, obtained in Dabob Bay.

Two other large oceanographic buoys are now in existence or under construction. One is in use by the Musée Océanographique (French) in Monaco and is under the direction of J.-Y. Cousteau. It is moored at a station in the Mediterranean 80 km south-southeast of Monaco and is continuously manned by a crew of two and several working scientists. The buoy is of considerable size, permanently moored, and permanently in the vertical orientation.

Another buoy, closely similar to *Flip* in size and mode of operation and, like *Flip*, financed by the U. S. Navy, is now under construction in Florida, for use in the Atlantic by the Naval Ordnance Laboratory. It is called *Spar* (Seagoing Platform for Acoustic Research). It differs from *Flip* mainly in that it will be unmanned. A connecting cable from the tending ship will carry power and all controls, including those for change of attitude. Data from instruments carried by the buoy will also be transmitted by cable to the tending ship and recorded there.

Description

The general configuration of the buoy can be seen in Fig. 1. The hull, 315 ft (95 m) long, is joined to a box-like structure which serves as a bow when the buoy is horizontal and as a superstructure when it is vertical. The overall length is 108 m; normal draft is 90 m when vertical, 4 m when horizontal. The cross section of the hull is everywhere circular; cylindrical sections, 20 ft (6.1 m) and 12.5 ft (3.8 m) in diameter, are joined by a tapering conical section, as shown in the figure. Transverse bulkheads form compartments and some of these are further subdivided longitudinally into top and bottom parts. Tanks 3, 5, and above are capable of withstanding full sea pressure at their operating depths, while tanks 1, 2, and 4 are free-flooding and never subject to large pressure differences. Figure 2 shows a number of external views.

The superstructure contains, in addition to fuel and freshwater tanks, four compartments which are used in both horizontal and vertical positions and constitute the inhabited part of the buoy. In the vertical position, the interior deck area has a maximum width of about 8 m and depth varying from 3 m to 4.5 m. There are also exterior platforms 2.5 m by 8 m at three of the superstructure levels. The compartments, in ascending order, are used for machinery, living space, and electronics laboratory, with the uppermost space housing air compressors and also serving as a "wet lab." When demand is high, all of the uppermost three compartments provide places to sleep.

Weight of the structure and equipment, including normal fuel and freshwater, is 590 tons (metric). In towing position, free-flooded and ballast water increase the total displacement to 1500 tons; and in the vertical position, to 2100 tons. Sixty-three tons of concrete ballast are placed off-axis to assure proper orientation when the buoy is horizontal. Buoyancy and attitude are controlled by flooding and venting, or by blowing, certain ballast tanks. The necessary piping runs to a control station on the exterior platform at the laboratory level. Receivers for compressed air are located in the upper part of the hull; their total capacity is approximately 113 m^3 of air at a maximum gauge pressure of 17 bars. The flood valves are operated by a hydraulic system.

The largest need for power is for the two air compressors. This is supplied by either of two 60-kw diesel-driven generators. A smaller 20-kw generator is sufficient for lighting, experimental, and most other uses.

The buoy has no self-propulsion, but is fitted with two propellors mounted near the center of the hull which are driven by servo-controlled hydraulic motors (30 kw) and provide sufficient tangential thrust to maintain the buoy in any desired azimuth against disturbing torques caused mainly by the wind.

A gyro-compass, a small radar, and radio transceivers are permanent equipment. A sonar system is currently being added.

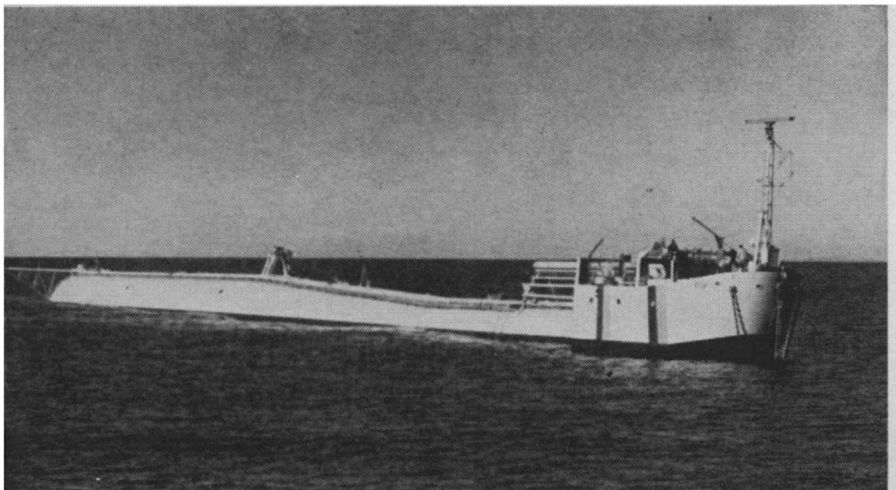
In order to accommodate operation in both orientations, the air compressors and the diesel-generator sets are mounted in gimbals, as is a major unit in the galley which includes range, refrigerator, and shelves. The mast is also capable of two orientations. It was originally envisioned that *Flip* would be boarded only after having been towed to the station where she was to be brought to the vertical. However, the provisions for use in both orientations proved so successful, and the ride on *Flip* under tow so comfortable, that both crew and scientific party stay aboard throughout normal operations, and people are transferred at sea only when required by some special circumstance.

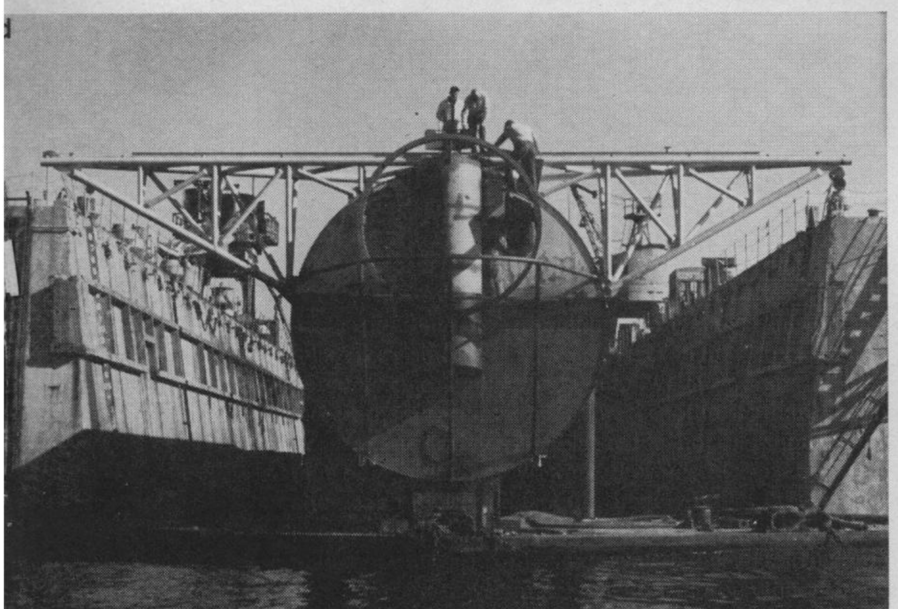
A transverse boom 15 m long, located at the extreme lower end of the hull, serves to mount a horizontal array of hydrophones. To permit precise comparison of orientation between these hydrophones and other apparatus at the upper end of the structure, a clear optical path is available along the axis of the hull for its full length, for the most part within tubes of diameter 30 cm to 90 cm. A precise polarimetric method of making the comparison of orientations is under development.

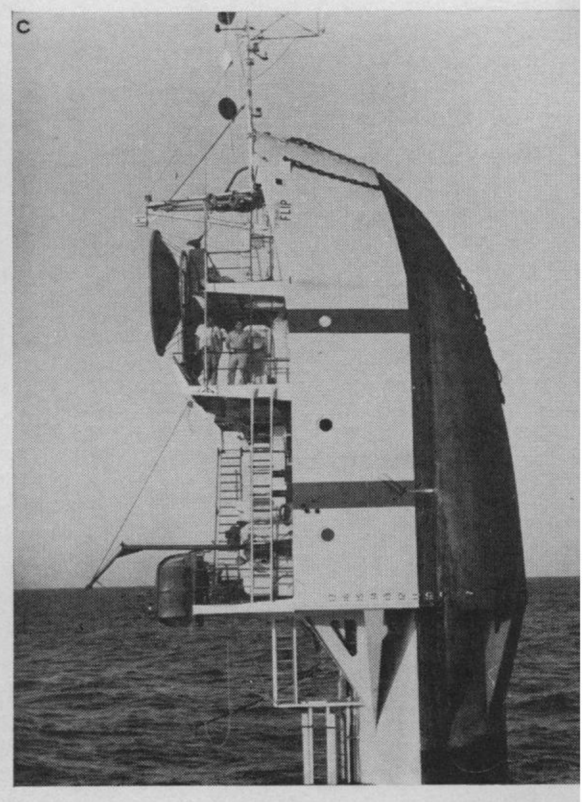
Flip is manned by a crew of seven, including the captain. Except for the cook, each man is qualified to perform all essential functions, including control of change of attitude. They are chosen, however, to form three two-man watches, with engineering and deck departments represented on each.

A number of views of *Flip* are shown in Fig. 2.

The process of changing orientation has proved simple and expeditious in practice. The change in either direction, once initiated, takes about 15 minutes. The start is very slow, and most of the time is used to reach the half-







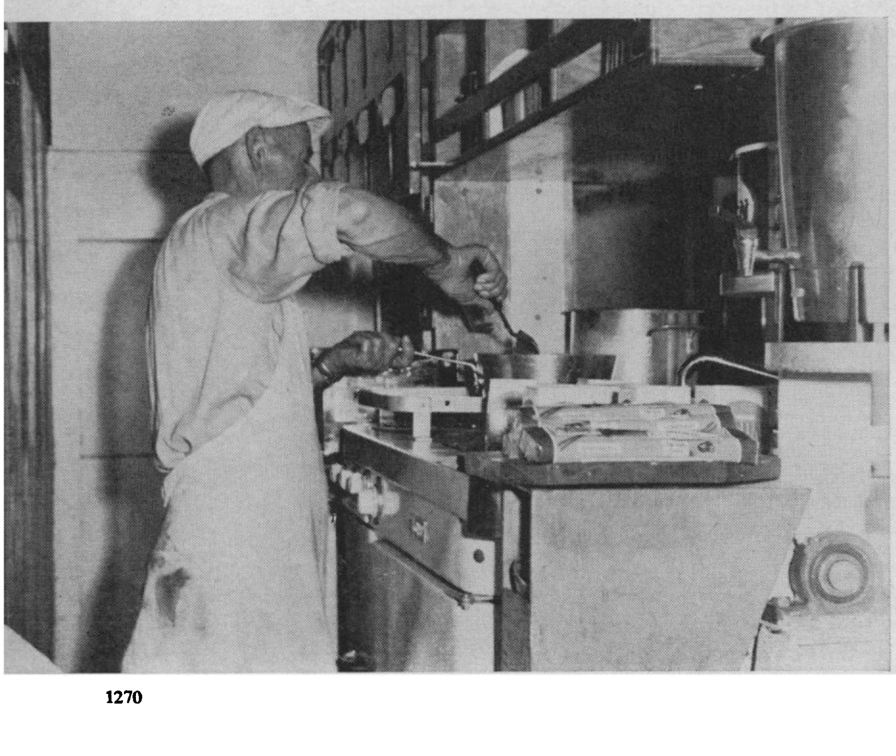


Fig. 2. Views of *Flip*. *a*, In horizontal position. Structure amidships carries propellors for control of azimuth when vertical. *b*, Coming to the vertical position. *c*, In vertical position. Shows most recent equipment. *d*, Stern view showing hydrophone boom and circular sonar array. *e*, Galley, showing gimbal (lower right).

way, 45-degree position. The later phase of motion involves increasing accelerations through a range of unstable positions; the second 45 degrees is traversed in 1 to 2 minutes.

Seaworthiness and habitability have more than met expectations. Both the crew and scientific parties have tended to be larger than originally contemplated, and, if the buoy were redesigned, space below the waterline would probably be more fully used. Although no extremely severe weather has as yet been encountered, no problems of safety are anticipated.

Figure 3 is a photograph taken from *Flip*, showing another research vessel of Scripps Institution, of conventional kind and size, during what might be called ordinary heavy weather (wind speed 20 m/sec). In contrast to the behavior of the ship shown, the motions of *Flip* in this kind of weather are just perceptible. She offers much superior working (and living) conditions.

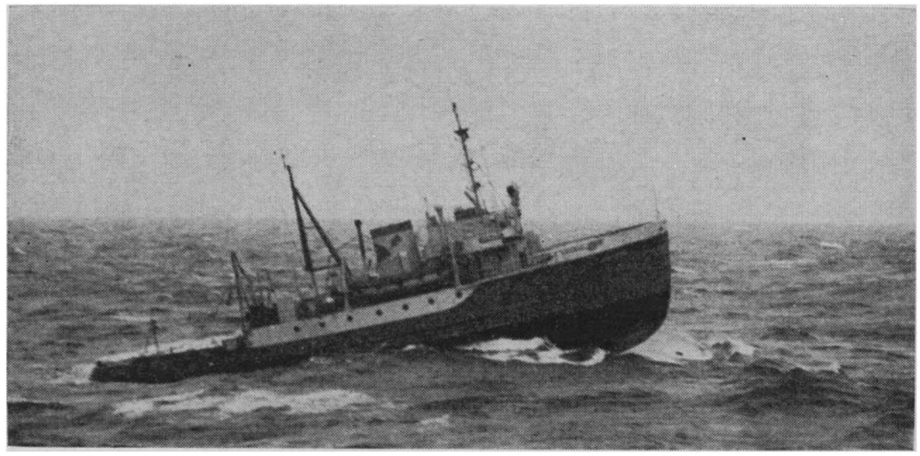


Fig. 3. Research vessel *Horizon*, seen from deck of *Flip*.

Response to Waves

Both the water motions and variations of pressure in ordinary sea waves have their greatest amplitude near the surface; each frequency component decreases exponentially with increasing depth at a rate determined by its wavelength. At a depth equal to one-half wavelength the amplitude is less than 5 percent, and at one wavelength, less than 0.25 percent, of the value at the surface. Thus a simple cylindrical buoy, floating vertically and supported by pressure against its bottom surface, will experience variations in vertical force due to wave pressure only to the extent that wave action penetrates to the depth of the bottom of the buoy. The first design criterion for vertical stability is a sufficient length, or draft.

The design of *Flip* was also influenced by concern for the natural frequency of vertical oscillation. For a uniform cylinder of 91-m draft, this frequency is 0.052 cy/sec (or a 19.2-second period). Long period swell may contain this frequency in appreciable amount, and for this component the resonant response of the buoy will have an amplifying effect which may more than offset the wave pressure reduction with depth, which in this case is to 37 percent of the surface value. In order to lower the vertical resonant frequency, *Flip* was given a reduced cross section at the waterline, which reduced the restoring force for vertical displacement and resulted in a natural frequency of 0.037 cy/sec (27-second period), which is comfortably beyond the limit of substantial intensity in the wave spectrum.

This variation in cross section introduces another factor into the behavior of the vertical component of motion. The bottom is no longer the only surface which experiences vertical pressure forces. There is necessarily a shoulder at some intermediate depth or depths on which downward pressure forces act, and waves of the higher frequencies will act primarily on this surface rather than on the bottom, since, although it has the lesser area, it is closer to the sea surface. There is, furthermore, a critical wave frequency for which the rate of attenuation with depth just offsets the ratio of these two areas and results in wave-generated forces, upward on the larger bottom area and downward on the smaller shoulder, which exactly cancel one another. This null frequency is always higher than the resonant frequency. For *Flip* the shoulder has 61 percent as much area as the bottom and is at a mean depth of 32 m. The null frequency is about 0.046 cy/sec (21.6 second period).

The composite outcome of these factors can be a substantial attenuation in the vertical motion of a buoy such as *Flip*, compared with that of the sea surface waves. Much less attenuation of motion is available in a horizontal direction. The near-surface horizontal components of wave motion necessarily affect the buoy directly. Reduction of the hull cross section in the wave zone and substantial extension of the hull into the quiet region below are both helpful but are not, in configurations comparable to *Flip*, able to prevent the buoy from participating substantially in the horizontal components of wave motion. Fortunately, the motion is least at the lower end of the buoy. It is also fortunate that vertical stability is usually the more important property for an oceanographic platform.

The most extensive observations thus far made of the behavior of *Flip* in the presence of waves were taken during September 1963, when she maintained a position in the mid-northern Pacific (near 40°N, 150°W) for the full month, instrumented with wave pressure recorders at 31-m and 88-m depths, and accelerometers (mounted in the laboratory) recording three components of acceleration. Analysis of the data is not yet complete, but some of the more evident aspects of the results are presented here for the first time (*5*).

A set of records (run 14) made during a 29-minute period which began at 7:00 a.m., 6 September 1963, at 39°39′N, 148°10′W, will be quite fully described, as a somewhat randomly chosen example. The wind speed was 5.8 m/sec and its direction 220 deg (clockwise from north); the heading of *Flip* (azimuth of keel) was upwind. A record based on noninstrumental observations gave the direction of the sea as from 220 deg and 265 deg, and the maximum wave height 2 to 3 m (trough to crest).

Power spectra have been computed to a maximum frequency 0.25 cy/sec. Integrated values representing variances of the corresponding records and the corresponding standard deviations are: for the pressure given by a sensor attached to *Flip* at 30.5-m depth, 287

cm^2 and 16.9 cm; for the vertical acceleration, 2.43 gal^2 and 1.56 gal (or cm sec^{-2}); for the transverse horizontal acceleration (indicated), 380 gal^2 and 19.5 gal; and finally for the corresponding fore-and-aft component, 274 gal^2 and 16.5 gal. Figure 4 shows the first two of these spectra, the sum of the third and fourth, and some related quantities.

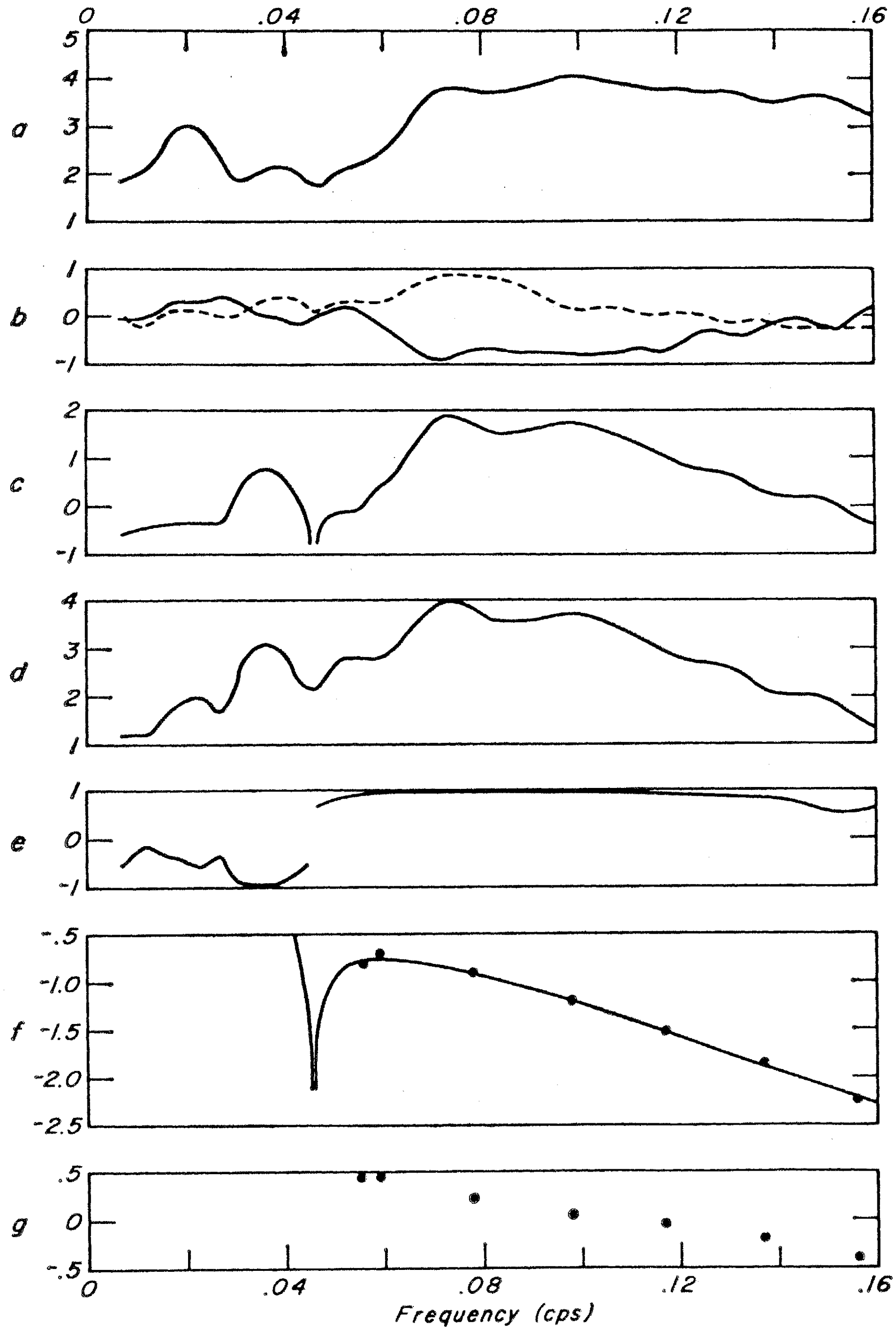


Fig. 4. Spectra showing response of *Flip* to waves. Quantities with * are plotted as logarithms to base 10. *a*, Sum of power spectra of two indicated horizontal components of acceleration, in gals squared per cycle per second. *b*, Solid curve: in-phase correlation coefficient between transverse and fore-and-aft components of horizontal acceleration (nonlogarithmic). Positive correlation associates forward and leftward components. Dashed curve: ratio of power spectral densities, transverse to fore-and-aft component. *c*, Power spectrum of vertical component of acceleration in gals squared per cycle per second. *d*, Power spectrum of pressure at a depth of 31 m, in square centimeters (of sea water) per cycle per second. *e*, In-phase correlation coefficient (nonlogarithmic) between records which yielded *c* and *d*. Positive correlation associates pressure increase with downward acceleration. *f*, Ratio of amplitudes, *Flip* displacement to sea surface displacement. Points: measured values, from *c* and *d*. Curve: calculated from theory. Ratio should be positive above 0.046 cy/sec and below 0.037 cy/sec (not shown), negative between. *g*, Measured amplitude ratio, indicated horizontal displacement of *Flip* laboratory to sea surface displacement, from *a* and *d*.

The horizontal accelerometers are of course sensitive to tilt, and indicate any changes in tilt of the buoy as well as true acceleration. These two parts of the measured values are not separated in Fig. 4, nor in the integrated values given above, but are left together and called an indicated acceleration.

The total indicated horizontal acceleration is of the order of a few hundredths of the gravitational acceleration *g* and is contributed in roughly equal amounts by the two horizontal components. Computation (but not thus far measurement) indicates that roughly four-fifths of the amplitude of indicated horizontal acceleration arises from true acceleration, and the rest is the result of tilt. On this basis the root-mean-square fluctuation in tilt is of the order of 0.3 deg. For the heaviest weather encountered during the month of observation, the corresponding estimate is 0.5 degree. Figure 3 was taken at that time; the marked contrast with an ordinary oceanographic vessel has already been noted.

The total vertical acceleration is of the order of one one-thousandth of *g*, or about one-twentieth of the horizontal acceleration. The spectrum of the vertical component does not extend as strongly toward high frequencies as does the horizontal, in accord with expectations.

For frequencies above 0.05 cy/sec, the vertical motion of the buoy is much smaller than that of the waves, and the recorded pressure fluctuations can be ascribed almost wholly to the waves. In this frequency region the similarity of the spectra of pressure and vertical acceleration, the high correlation between these variables, and the sign of the correlation are all consistent with a model in which the acceleration is caused primarily by wave pressure acting on the conical shoulder of the hull.

The lower frequency parts of the spectra in Fig. 4, *a*, *c*, and *d*, indicate three critical frequencies, which occur at values close to those arrived at by calculation. At 0.046 cy/sec the null in the spectrum of vertical acceleration, described above, is accompanied by a sharp reversal of sign of the correlation with pressure. At 0.037 cy/sec, vertical oscillation of the buoy at its natural frequency gives rise to peaks in the spectra of vertical acceleration and of pressure. The area under the first peak corresponds to a root-mean-square acceleration of 0.218 gal associated with the resonance, corresponding to a root-mean-square vertical displacement of 4.04 cm. The area under the peak of the pressure spectrum gives 3.19 cm. These two results are considered consistent in the circumstances. The natural frequency of tilt, or roll, at 0.021 cy/sec is shown by the peak in the horizontal acceleration spectrum. The area under this peak indicates an apparent root-mean-square acceleration of 3.16 gal, which arises almost wholly from tilt of root-mean-square magnitude of about 0.185 deg. The corresponding horizontal displacement of the accelerometer is 20.9 cm, relative to the center of inertia at 55-m depth.

From the ratio of the observed spectra of vertical acceleration and of pressure, one may calculate the amplitude ratio of vertical buoy displacement to sea surface displacement as a function of frequency. In Fig. 4*f*, values of this ratio are plotted and compared with a curve derived from theory (*2*). Figure 4*g* shows experimental values for the corresponding ratio of apparent horizontal buoy displacement (treating the measured horizontal acceleration as wholly true acceleration) to sea surface displacement. These observations are of the expected order of magnitude; detailed comparison with theory has not yet been made.

The foregoing does not touch on the role played by drag forces in the buoy motion. The analysis of phase relations which bears on this point has not been completed, but preliminary indications are that for the most prominent frequencies vertical motion lags a little (probably less than 10 deg) behind the pressure forces, while the horizontal motion shows somewhat greater lags (perhaps 20 to 30 deg). High resolution spectra obtained by Snodgrass *et al.* (*3*) show a 14-fold rise of amplitude at the vertical resonance, and it is probable that the true corresponding rise for the horizontal resonance is greater than 3.8, which is the value obtainable from the spectrum shown in Fig. 4*a*.

The precision study of acoustic arrivals which generated the plan to construct *Flip* has already been mentioned. This work continues to hold first priority, but other instances of her particular usefulness for specific oceanographic investigations have appeared and should continue to appear in increasing abundance as our experience grows and broadens.

The expedition of September 1963 provides several examples. Its primary purpose was to enable *Flip* to be used in a project undertaken by a group working in the Institute of Geophysics (University of California, San Diego) (*3*). A series of stations from New Zealand to Alaska was established for the simultaneous observation of long-period ocean wave groups as they move across the Pacific from stormy areas of generation in the Antarctic. These workers have developed a technique of remarkable sensitivity and precision for the measurement of ocean wave spectra which has always heretofore required a bottom-mounted pressure sensor. *Flip* enabled them for the first time to apply this technique at a mid-ocean station. They obtained meaningful spectra from *Flip* for frequencies above 0.04 cy/sec with the use of pressure measurements alone. It is altogether probable that, with the help of buoy acceleration measurements, the wave observations can also be extended to lower frequencies.

The horizontal accelerations of *Flip* also may be a new source of information about the directions of arrival of ocean waves, even though the amount of such information to be expected from any point-receiver is inherently rather limited. Several wave-groups which were identified by Snodgrass *et al.* as having originated in the Antarctic were found to give confirmatory indications of arrival direction in the horizontal acceleration spectra. These spectra generally show features suggesting that they may be composed of arrivals from different well-defined directions. For example, Fig. 4*b* shows regions of high correlation between components, in which three rather distinct component amplitude ratios are seen (around 0.08, 0.10, and 0.115 cy/sec). Similarly, the behavior at the tilt resonant frequency in the cases so far evaluated shows a variety of component amplitude ratios and a number of comparatively high correlation values of both signs (of eleven, six were numerically greater than 0.2 and ranged from −0.2 to −0.48 and from +0.2 to +0.71). The possibility that this tilt resonance is acting as a sensitive amplifier of very low-level, low-frequency water wave motion will be carefully investigated.

Other instrumentation on *Flip* during the September expedition was a set of temperature-measuring elements spaced at intervals of 3 m at depths from 0 to 90 m. These yielded during the month probably the most extensive, continuous, and detailed record of its kind that has ever been obtained from one position in the open ocean. These data are being examined primarily for information on internal waves (*4*).

During the expedition *Flip* was allowed to drift continuously for 27 days. In this time her position changed by 60 miles, the displacement being toward the southwest. In view of the prevailing westerly winds and the known eastward surface currents in the ocean in this area, the direction of drift was wholly unexpected. This highlights a situation of which oceanographers are perhaps more aware than others: even in the most accessible upper layers of the ocean, there is much yet to be discovered and even more awaiting full investigation and understanding.

References and Notes

1. F. H. Fisher and F. N. Spiess, *J. Acoust. Soc. Am.* **35**, 1633 (1963).
2. A treatment of theory (which I have incorporated in internal memoranda of this laboratory) will accompany the full report on the experimental data here described. Similar cases are treated theoretically by J. N. Newman, *David Taylor Model Basin Rept. No. 1499* (Washington, D.C., May 1963); and R. Taussig, *David Taylor Model Basin Rept. No. 1673* (Washington, D.C., 1963).
3. F. E. Snodgrass, G. W. Groves, K. F. Hasselmann, G. R. Miller, W. H. Munk, W. H. Powers, report in preparation.
4. M. K. Robinson, report in preparation.

5. The results given in this section are part of the research sponsored by the Office of Naval Research under contract Nonr 2216 (05).