SECOND YEAR INTERIM REPORT

on

EDINBURGH WAVE POWER PROJECT

"STUDY OF MECHANISMS FOR EXTRACTING POWER FROM SEA WAVES"

September 1976

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Overall schema of the electronic systems
Wave height measurement techniques
The heaving float wave gauge
The two-wire resistive wave gauge
The quadrilateral linkage wave gauge
Transducer conditioning amplifiers
The standard power amplifier
General dynamics control circuit
Switchable changes to Dynabox characteristics
The backbone pitch simulation
The mixed spectrum generator
Wave power measurement in a narrow tank (the \( H^2 T \) box)
Long-term averaging technique
Peak and average reading force meter
Variable phase l.f. oscillator with synchronisation input
The general purpose multiplier
The duck efficiency meter
The synchronised oscilloscope system
The ramp generator
The multiplier
The Z modulator
Objectives for 1976/77
Photographs
References

Cover

The cover of this report shows heave and surge forces on a cylinder during the
the passage of a single wave. The wavelength was 15.6 diameters, the depth of
immersion of the axis was .4 diameters. The wave amplitude increment was one
hundredth of a diameter. The heave force sensitivity was twice that of the surge.
Introduction

I am very happy to report that Mr. Jeffrey has been making a steady recovery from the illness which left him paralysed last August. He returned to work in January of this year and is now nearly fit again.

Most of our work this year has been the measurement of backbone forces on single models in a narrow tank. The results form a large part of this report. We have found some unexpected behaviour of the heave forces on cylinders which may prove of interest in other areas.

The efficiency of ducks on the surge-heave rig is encouraging. Although we do not yet know the dynamic characteristics of the final backbone design it looks as though some movement can occur without much ill effect.

We could easily spend at least another year making measurements in the narrow tank, but we have decided that backbone behaviour in short-crested seas is now of greater importance. Development of experimental techniques in the field will be the major part of our work in 1977.

The cost estimates for the period up to October 1976 proved accurate.

On the basis of two years' work and the results of the Lanchester team with the free floating string we can say that the possibility of economic power from sea waves has still not been excluded.

The wave power team would like to record their gratitude for the foresight, generous support and understanding of the Department of Industry. We hope that the future under the direction of the Department of Energy will be equally happy.

S.H.S.

30th September 1976
FORCE MEASUREMENTS

A well established equation for fluid loading is based on the work of Morison. The equation separates the forces on objects into two kinds. One kind, the drag term, depends on the square of wave height and the object's projected area. The other, the inertial part, depends on the first power of wave height and the object's volume. The characteristics of a particular shape are expressed in the coefficients $C_m$ and $C_d$. Wiegel explains its use on page 253 of his book Oceanographical Engineering. For the horizontal force (which we would call surge) he gives

\[ F_h = -2\pi^2 C_m \rho V \frac{H^2}{T^2} \sin \frac{2\pi t}{T} \left( \cosh \left[ \frac{2\pi (y+d)}{L} \right] / \sinh \frac{2\pi d}{L} \right) \sin 2\pi t \]

\[ + \frac{1}{2} C_d \rho A \frac{H^2}{T^2} \left( \cosh \left[ \frac{2\pi (y+d)}{L} \right] / \sinh \frac{2\pi d}{L} \right)^2 \cos \frac{2\pi t}{T} \frac{\cos 2\pi t}{T} \]

- $t$ is the instant in time
- $\rho$ is the density of water
- $V$ is the volume of the object
- $A$ is its area
- $H$ is the wave height from trough to crest
- $T$ is the wave period
- $y$ is the depth of immersion measured negatively downwards from the surface to some representative point on the object
- $d$ is the depth of water
- $L$ is the length of wave
- $C_m$ and $C_d$ are the mass and drag coefficients of the shape in question.

Give or take a sinh, the vertical forces are similar. Wiegel warns that the equation refers to fixed submerged bodies with dimensions small compared to wave length. Our ducks are tested in waves with lengths ranging from 5 to 25 duck diameters, so that at high frequencies we cannot say that they are very small compared to wave length. As forces change with depth there is some question about the position of the point to which $y$ is measured. Ducks are not submerged and they are not rigidly held, and so we should not use Morison's equation without some careful consideration.
A Declaration of Heresy

Any decent coefficient should be invariant for the shape it describes, at least over a certain range of conditions, and its usefulness declines in proportion to the amount that it actually does vary and the complications of deciding whether or not one is in the right range. Wiegel (on page 258) shows some experimental measurements for the value of $C_d$ for various sizes of round pile. For any one model they can be distributed over a range of nearly ten to one. On page 260 he shows values of $C_m$ which swing from +2 to -2 during the wave cycle. One example of this is shown on page 11.5 of this report. There is no way in which the equation can be made to show responses at twice the wave frequency or to deal with the non-linearities which occur as soon as the forces become large enough to be dangerous.

If one has to define wavelength to diameter ratio, wave height to diameter ratio, depth of immersion to diameter ratio, water depth to diameter ratio, and even barnacle size to diameter ratio in order to get a value for a coefficient which changes through the cycle, then the whole business is a waste of time. Agershou (2) does a statistical analysis of values of mass and drag coefficients just as if they were wave heights or gas molecule velocities. Water is not like that. During this year we have seen some pretty weird effects but, given a stable wave-maker, the waves repeat their anomalies with a deadly precision. We should not fool ourselves into thinking that we understand fluid loading by using a complicated equation and concealing our ignorance in the uncertainty of a coefficient.

Instead of trying to find values for the elusive coefficients, we have decided to present the experimental data in a form in which all the warts will be revealed. With the use of a specially designed oscilloscope time base, we have been able to superimpose many traces to show the amplitude phases and harmonic content of various parameters. We have produced sets of families of curves to show particular points.

We have also produced a new equation for fluid loading which is reserved purely for duck and cylinder shapes in wavelength to diameter ratios likely to be used for wave power. It is designed for easy use and instant mental calculations in a much more restricted range of conditions than the universal Morison calculation.

The New Equation

Both inertia and drag terms in Morison's equation point to forces rising with the cube of scale. They make forces be proportional to the density $\rho$ of the fluid. It is reasonable to suppose that for long strings of ducks or single ducks in narrow tanks the forces will be proportional to the width $W$ of the duck. Our tests show that forces are proportional to wave height $H$ rather than its square, and so we would argue that the inertia terms dominate the drag terms. This is supported by most guesses for values of $C_m$ and $C_d$.

The problems arise when it comes to the frequency dependence of the force. Both drag and inertia expressions include $1/T^2$ which would make the forces rise with increasing frequency. But this is countered by the presence of $y$ in the coss parts which makes the forces fall as the wavelength $L$ gets less. To make Morison's equation work you have to chop the section into slices parallel to the water surface and use a separate value of $y$ for each slice.

If one examines the results of force measurements for ducks it is clear that the forces reach their maximum value in the middle of our frequency range and fall rather gradually on either side. For example, look at the results for D0018 at 1 Hz on page 3.4 and the overview shown on page 15.2.
Even more interesting are the results for the smart version of DO018 shown in the series on page 5.1 onwards. There is very little variation in force from .85 Hz to 1.8 Hz covering wavelength to diameter ratios of 20 down to 5. It would be reasonable to express the forces in terms of a single force coefficient which would be a function of shape and L/D ratio. Its value would not change much as L/D moved through the range of interest.

We can now try to write the equation. It must have $W$, $Y$ and $H$ at the first power. It must rise with the cube of scale. It must depend on duck diameter $D$ to some power and its dimensions must agree. Let's try

$$F = W Y g D H C_f(L/D)$$

Values for $C_f$ are given for one duck on page 2.4. Good ducks have $C_f$ less than .5. There are some more curves on page 12.1.

The acceleration of gravity $g$ has to be included to make the dimensions correct. It does not appear in Morison's equation while it does appear in the results of both Archimedes and Longuet-Higgins on buoyancy and radiation stress respectively.

This $C_f$ is the modulus of the force for the stress man who cares more about failure than phase. If we take phase sensitive measurements from our transfer function analyser we can resolve the forces on a model into real and imaginary parts. We can use these to calculate $C_f$ real and $C_f$ imaginary for the dynamicist. We can also measure higher harmonic components and so cater for some of the non-linear effects. This would require measurements at particular values of $H/D$ and well as $L/D$ ratio.

Practical engineers will imperialist inclinations will note that although the S.I. system gives the forces in Newtons, the factor $Y g$ is almost the same as the conversion between Newtons and Oldtons. If they should ever need to do fluid loading calculations while driving at high speed they could do worse than use the equation

$$\text{Force} = \frac{\text{Wave height} \times \text{duck diameter (in metres)}}{2} \text{ tons per metre.}$$

If it is true that force is proportional to diameter, rather than its square as a superficial glance at Morison's equation would suggest, then there are profound implications in design. The rigidity of tubes of constant wall thickness depends on the cube of the diameter. The rigidity of tubes of constant material content depends on the square of diameter. We should consider big thin-skinned ducks with their insides full of sea-water. At any rate the pressure to go very small is relaxed. Perhaps we should now take 15 metres as the probable size for the North Atlantic, rather than the 10 metres we were striving for. Confirmation of this theory at tenth scale is urgent.
COMPARISON OF 2 TYPES OF FORCE COEFFICIENTS
for a DUCK with a SMART DYNAMOMETER and one without

\[ \text{H/D} = 12 \text{ throughout} \]

<table>
<thead>
<tr>
<th>Type</th>
<th>Smart Duck</th>
<th>Stupid Duck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Door</td>
<td>0 2 1 4 2</td>
<td>3 5 4 5 0</td>
</tr>
</tbody>
</table>

1: MASS COEFFICIENT

2: FORCE COEFFICIENT

- a) IN SURGE
- b) IN HEAVE
- c) IN SURGE
- d) IN HEAVE

\[ \text{FREQUENCY (HERTZ for } D = 1 \text{m)} } \]

21/76
Conclusions

After a short period of work on fluid loading we feel rather as chemists did before Mendeleev. The experimental data in the next sections of this report cannot give a full picture of the effects of changing every variable. If the reader really wants to get an intuitive grasp we suggest that he dissects several copies of the report and pins sets of curves on the wall in domino pattern. If this is not possible then he should use the overviews containing miniatures and track down cross references. Trying to read the force data straight through is not recommended without psychiatric advice.

The points which seem important to us are as follows:

(1) It seems difficult to produce simple coefficients which allow force predictions from Morison's equation when objects break the surface and waves are large. Coefficients are strongly dependent on L/D ratio.

(2) A simple equation can be written in which there is less variation of the coefficient with L/D ratio. It has yet to be confirmed at another scale.

(3) The rise of force with frequency caused by the $1/T^2$ term is balanced by a fall due to the decay of orbital motion of the water with depth. Balance occurs at L/D ratios near 15 which is the 'interesting' part of the range and forces fall gradually to either side. (See pages 3.4 and 5.4)

(4) Surge forces are more orderly than heave forces which show reversal of phase and frequency doubling when cylinders are nearly awash. Depth of immersion has profound effects on heave force. (See pages 8.4 and 8.6.)

(5) Forces on objects with L/D between 20 and 5 and in waves with H/D up to .3 are proportional to wave height rather than its square.

(6) Duck forces are more orderly than cylinder forces. The surge behaviour is more similar than heave.

(7) The damping component of the power take-off mechanism has profound effects on heave force but not much on surge. (See page 6.1.)

(8) The spring component of smart power take-off has large effects on forces particularly at low frequencies. Negative spring rate reduces surge forces and increases heave. (See page 16.1 to 16.6.)

(9) Our favourite duck to date (the smart version of D001B) has equal surge and heave forces. This is a good thing and may not be a coincidence. (See page 5.1.)

(10) Direct radiation stress forces are not a serious threat particularly with hunch backed ducks. (See page 17.1.)

(11) Direct downward forces are large enough to demand attention.

(12) Water is a peculiar substance and waves are difficult to understand.
CONVENTIONS FOR FORCE MEASUREMENTS

Through historical accident we have always worked in test tanks where waves come from the right of the operator's test bench. We have the convention that horizontal forces along the tank are called surge forces, and, following the normal Cartesian convention, beachward forces are negative and plotted downwards in the photographs.

It is unfortunate that Wiegel was not informed of our practice in time to correct the proofs of 'Oceanographical Engineering'(1) and so the spatial convention of his figure 11.6 on page 254 may cause some confusion.

We define heave as positive up. We use the normal oscilloscope convention for the time axis with the start of a trace to the left.

We arrange for a delay in the oscilloscope trigger signal so that the trace always starts at the moment when the waterline would have passed through its mean position on the way up at the centre of cylinders or at the axis of rotation of ducks. These time delays are measured for each frequency and wave amplitude with the model removed from the tank. (Wave length is affected by wave amplitude.) This technique works well for models which do not reflect much energy. But if it were the case that reflections altered wave length it would be less satisfactory, particularly with the shorter wave lengths.

Wave amplitude is measured from mean water level to crest or trough. It is half the value of trough to crest height.

The oscilloscope sweep rate is set so that a full cycle of the wave takes ten divisions at all frequencies. The fly-back time is negligible so that each trace will leave the right hand side of the photograph at the same height at which it enters on the left. Circuit diagrams are on page 24.34.

We plan a test series so that the largest signals will be within the full-scale of the photograph and then stick to the same calibration throughout that set. This means that some measurements are made with rather a low sensitivity but it does help visual scanning of a group. In nearly every case the zero of force is the horizontal centre line of the photograph. Exceptions are clearly marked. All the tests were carried out in 0.6 M depth of water. This is certainly 'deep' for the higher frequencies but only a quarter of wave length at the bottom of our test range. It is probably close to our final full-scale conditions. The ratio $L'/L$ is given for the lower frequencies and is the ratio of the wave length in 0.6 M depth of water to that in deep water. It is calculated from the relation given by Wiegel (page 15, equation 2.43)

$$\frac{d}{L'} \tanh \frac{2\pi d}{L'} = \frac{d}{L}$$

Most of the work so far has been done with two duck models, (D0017 and D0018) and one cylinder. The base diameter of both ducks and the diameter of the cylinder were all 10 cm. The ratio of wavelength to this diameter (L/D) is the best indication of test conditions and is inserted wherever possible. Models are 29.5 cm long and are mounted square across the tank with the minimum clearance at each end. We argue that this will represent an element at the centre of a long string.

Damping settings used are those which we believe best for each duck. Some experiments with damping variation are given on page 6.1 of this report and page 6 of the first year report.
PHOTOGRAPH CODING
(See immediately above each photograph)

We have about a thousand force wave-forms to present which all look fairly similar. To avoid getting the photographs, ourselves or the reader mixed-up, we gave each photograph a permanent identification number as soon as it emerged from the camera. This is a serial number followed by the date which ties up with the tank log book. We also gave each photograph a code number containing information about the parameters, calibrations and variables in question. The reader need not attempt to decode this as the information is given more fully in the descriptions.

The letters on the photographs have the following significance:

\[
\begin{align*}
C &= \text{wave crest} \\
T &= \text{wave trough} \\
S &= \text{surge force (downward = beachward)} \\
\theta &= \text{nod angle} \\
H &= \text{heave}
\end{align*}
\]
SURGE AND HEAVE FORCES ON A MEDIUM BEAK DUCK AT .85 HZ

MODEL: DO018 (see p. 19.3) Pure damping 5.5 Newton cm/(radian/sec)

--- Surge force: 2 Newton per division

--- Heave force: 2 Newton per division

. . . . Nod reference for 1.2 cm wave: .2 radian per division
Frequency: .85 Hz. L/D = 21.6, L'/L = .950
Wave amplitude: 0 to 1.6 cm in .2 cm increments.

Surge force is much bigger than heave in a ratio of over 2:1.
Surge forces are beautifully linear with wave amplitude showing that we are well inside the inertia regime. But there is a small anomaly in the downward heave force at 200° of phase.
Surge and heave are nearly in antiphase.
This is the lowest frequency at which we could cover the range of amplitudes with Mark 1 wave-makers.

It is interesting to compare these curves with those on page 4.1 onwards for the shorter beaked DO017 which show a good deal more irregularity for higher waves.
Surge and Heave Forces on a Medium Beak Duck at .9 Hz

Surge force: 2 Newton per division
Heave force: 2 Newton per division
Nod reference for 1.2 cm wave: .2 radian per division
Frequency: .9 Hz, L/D = 19.3, L'/L = .966
Wave amplitude: 0 to 1.6 cm in .2 cm increments.

This is the same test as before but at .9 Hz. The surge force is bigger than at .85 Hz. There is still some negative heave anomaly around 200° phase.
SURGE AND HEAVE FORCES ON A MEDIUM BEAK DUCK AT .95 HZ

MODEL: D0018 (see p. 19.3) Pure damping 5.5 Newton cm/(radian/sec)

Surge force: 2 Newton per division

Heave force: 2 Newton per division

Nod reference for 1.2 cm wave: .2 radian per division

Frequency: .95 Hz. L/D = 17.3, L'/L = .977

Wave amplitude: 0 to 1.6 cm in .2 cm increments.

There is still a downward heave anomaly and a drop on the peak positive surge force in comparison with the .9 Hz value which is wrong for a 1/T^2 law.
SURGE AND HEAVE FORCES ON A MEDIUM BEAK DUCK AT 1 Hz

Surge force: 2 Newton per division
Heave force: 2 Newton per division
Nod reference for 1.2 cm wave: 0.2 radian per division
Frequency: 1 Hz. L/D = 15.6, L'/L = .985
Wave amplitude: 0 to 1.6 cm in .2 cm increments.

MODEL: D0018 (see p. 19.3) Pure damping 5.5 Newton cm/(radian/sec)

The very pronounced heave anomaly in this photograph seems to be moving back in time as the frequency rises. The surge peak at 250° phase looks bigger than at .95 Hz which is right for a 1/T² law.
MODEL: DO018 (see p. 19.3) Pure damping 5.5 Newton cm/(radian/sec)

Surge force: 2 Newton per division
Heave force: 2 Newton per division
Nod reference for 1.2 cm wave: 2 radian per division
Frequency: 1.2 Hz, L/D = 10.8
Wave amplitude: 0 to 1.6 cm in .2 cm increments.

The top two surge forces between 180° and 270° look tightly bunched. Surge is lagging in comparison with the 1 Hz curves and is now nearly 270° behind the heave force. Compare this with the .85 Hz test where they were about 180° apart. Nod reference seems to have moved very little in phase.
MODEL: D0018 (see p. 19.3) Pure damping 5.5 Newton cm/(radian/sec)

- Surge force: 2 Newton per division
- Heave force: 2 Newton per division
- Nod reference for 1.2 cm wave: .2 radian per division

Frequency: 1.4 Hz. L/D = 7.97
Wave amplitude: 0 to 1.6 cm in .2 cm increments.

The anomalous drop in heave force is now less than at the lower frequencies. There is some crossing and bunching of the surge signals at high waves, and a steady trend towards lower forces at higher frequencies contrary to the $1/t^2$ law. It is not possible to account for the differences in force between 1.4 Hz and 1.0 Hz (see page 3.4) using the

$$\frac{\cosh \left[ \frac{2\pi (y+d)}{L} \right]}{\sinh \frac{2\pi d}{L}}$$

unless you measure $y$ to a point absurdly far below the bottom of the duck.
We are using an odd frequency step because the wave length at 1.6 Hz is twice the tank width and cross waves develop very easily.

We are starting to get high frequency ripples, bunching and even crossing of the curves in comparison with the good behaviour at lower frequencies.
**SURGE AND HEAVE FORCES ON A MEDIUM BREAK DUCK AT 1.8 Hz**

**SF HF (2N) D 1.8 Hz 0 x 2 - 1.6 amp**

**MODEL:** D0018 (see p. 19.3) Pure damping 5.5 Newton cm/(radian/sec)

---

**Surge force:** 2 Newton per division

**Heave force:** 2 Newton per division

**Nod reference for 1.2 cm wave:** .2 radian per division

**Frequency:** 1.8 Hz. L/D 4.82

**Wave amplitude:** 0 to 1.6 cm in .2 cm increments.

---

This is the top end of the frequency range. There is a lot of ripple particularly in the wave trough. Possible causes are examined on page 18.1. It proved to be something in the wave-maker.

Comparisons with other models are given on pages 14.1 and 15.1.
SURGE AND HEAVE FORCES ON A SHORT BEAK DUCK AT .85 Hz

MODEL: D0017 (see page 19.2) Pure damping 2.5 Newton cm/(radian/sec)

--- Surge force: 2 Newton per division

........ Heave force: 2 Newton per division

. . . Nod reference for 1.2 cm wave: .2 radian per division

Frequency: .85 Hz. L/D = 21.6, L'/L = .950

Wave amplitude: 0 to 1.6 cm in .2 increments.

In contrast to the medium beak duck D0018 on page 3.1 there is considerable irregularity between 180° and 300°. The higher surge forces are bunched and the downward heave forces show a peak instead of the collapse of D0018. Note the 50% increase of nod amplitude because of the shorter beak but nod phase is very similar. We find that 'clean' force signals can be made to repeat from day to day. On page 18.2 there is a demonstration of repeatability. The anomalies are not so reproducible. Forces during the wave trough seem to be dirtier than those in the crest.
SURGE AND HEAVE FORCES ON A SHORT BEAK DUCK AT .9 HZ

Surge force: 2 Newton per division
Heave force: 2 Newton per division

Nod reference for 1.2 cm wave: .2 radian per division
Frequency: .9 Hz, \( L/D = 19.3, L'/L = .966 \)
Wave amplitude: 0 to 1.6 cm in .2 cm increments.

There is less anomalous behaviour in surge at 250° but still some bunching. Downward heave forces are larger than for the long beak D0018 on page 3.2.
SURGE AND HEAVE FORCES ON A SHORT BEAK DUCK AT .95 HZ

SF HF (2N) D .95 HZ 0 x .2 - 1.6 amp

MODEL: D0017 (see p. 19.2) Pure damping 2.5 Newton cm/(radian/sec)

- Surge force: 2 Newton per division
- Heave force: 2 Newton per division

... Nod reference for 1.2 cm wave: .2 radian per division

Frequency: .95 Hz. L/D = 17.3, L'/L = .977

Wave amplitude: 0 to 1.6 cm in .2 cm increments.

The anomalies seen in the .85 Hz test on page 4.1 which were reduced at .9 Hz have reappeared. Indeed, this picture looks very like the .85 Hz results.
SURGE AND HEAVE FORCES ON A SHORT BEAK DUCK AT 1.0 Hz

MODEL: D0017 (see p. 19.2) Pure damping 2.5 Newton cm/(radian/sec)

Surge force: 2 Newton per division
Heave force: 2 Newton per division
Nod reference for 1.2 cm wave: .2 radian per division

Frequency: 1.0 Hz. L/D = 15.6, L'/L = .985
Wave amplitude: .2 to 1.6 cm in .2 cm increments.

It is interesting to compare these cleaner surge forces with those of the medium beak D0018 at the same frequency on page 3.4. The nod reference is moving back in phase in comparison with the lower frequency tests in this series, but so far it has been very steady in amplitude.
MODEL: D0017 (see p. 19.2) Pure damping 2.5 Newton cm/(radian/sec)

Surge force: 2 Newton per division
Heave force: 2 Newton per division
Nod reference for 1.2 cm wave: .2 radian per division

Frequency: 1.2 Hz. L/D = 10.8
Wave amplitude: 0 to 1.6 cm in .2 cm increments.

This is supposed to be the best frequency (peak efficiency) for D0017.
SURGE AND HEAVE FORCES ON A SHORT BEAK DUCK AT 1.4 HZ

MODEL: DO017 (see p. 19.2) Pure damping 2.5 Newton cm/(radian/sec)

- Surge force: 2 Newton per division
- Heave force: 2 Newton per division

Nod reference for 1.2 cm wave: .2 radian per division
Frequency: 1.4 Hz. L/D = 7.97
Wave amplitude: .2 - 1.6 cm in .2 cm increments.

While it is common for the higher force signals to bunch, this picture shows some signs of spreading in peak heave forces. See also page 10.2.
Surge and Heave Forces on a Short Beak Duck at 1.8 Hz

Model: DO017 (see p. 19.2) Pure damping 2.5 Newton cm/(radian/sec)

- Surge force: 2 Newton per division
- Heave force: 2 Newton per division
- Nod reference for 1.2 cm wave: 0.2 radian per division

Frequency: 1.8 Hz, L/D = 4.82
Wave amplitude: 0 to 1.6 cm in 0.2 cm increments.

At the larger amplitudes there is quite a lot of high frequency reflection. There would have been less if we had included some negative inertia term in addition to the pure damping of the power take-off. The apparent phase jitter may have been caused by the difficulty in setting accurate trigger delays (see page 2.3) with so many waves and so much reflection in the tank. The nod reference was getting lost so we did a repeat trace above.

Comparisons with other ducks and some cylinders are given on page 15.1.
The whole of this series shows an interesting departure from the set shown on pages 3.1 - 3.8. There has been a reduction in waveward surge force during the trough and an increase in downward heave and nod angle. Heave and surge forces are closer in amplitude for lower amplitude waves. There is a collapse in the waveward surge force at the highest amplitude. This sort of irregularity is quite consistent from wave to wave but not from day to day, and we should be cautious about cutting strength requirements. Nevertheless, anomalies which reduce forces are more common than those which give an unexpected peak.
Surge and heave forces on a medium peak duck with a smart dynamometer at .9 Hz

Surge force: 2 Newton per division
Heave force: 2 Newton per division
Nod reference for 1.2 cm wave: .2 radian per division
Frequency: .9 Hz. L/D = 19.3, L'/L = .966
Wave amplitude: 0 to 1.6 cm in .2 cm increments.

This is very similar to the .85 Hz results. There is the same balance between heave and surge and the same slewing over of the top two downward forces. These must be investigated with bigger waves. Nod amplitude is rising with frequency.
This photograph shows the highest value of nod amplitude for this series. It is also the first case of a duck showing a larger force in heave than surge. Notice the rapid fall in nod position compared with the slower rise. This can also be seen in a larger instantaneous power level as shown in the photograph on page 16.3. We have done some preliminary tests with changes to the symmetry of torque command signals. Small improvements in efficiency are combined with a more even duty cycle in the dynamometer. This would be an excellent area for investigation during the 1980s.
MODEL: DO018 with -3.5 N cm/rad, 4.5 cm/(rad/sec), -2 N cm/(rad/sec^2)

- Surge force: 2 Newton per division
- Heave force: 2 Newton per division
- Nod reference for 1.2 cm wave: .2 radian per division

Frequency: 1.0 Hz, L/D = 15.6, L'/L = .985
Wave amplitude: 0 to 1.6 cm in .2 cm increments.

The surge forces have grown marginally compared with .95 Hz, the heave forces are a little smaller. The upward heave forces are very flat topped. Nod amplitude is now falling with frequency. Is the peak of nod amplitude a pointer to the optimised frequency? It would be for linear filters in electronics.
Waveward surge forces seem to be falling as frequency rises. Nod amplitude continues to fall. The slewed downward heave forces of the lower frequencies of this series are developing into the heave anomaly seen in the series with pure damping shown on page 3.3.
As we approach the top end of the frequency range the smart dynamometer is less useful in efficiency improvement and we see that there is less difference in force behaviour between this and the equivalent model with pure damping.

In the first year of the project we regarded 1.4 Hz as the middle of the test range.
Surge and heave forces on a medium break duck with a smart dynamometer at 1.55 Hz

Surge force: 2 Newton per division
Heave force: 2 Newton per division
Hod reference for 1.2 cm wave: .2 radian per division
Frequency: 1.5 Hz. L/D = 6.50
Wave amplitude: 0 to 1.6 cm in .2 cm increments.

This is practically indistinguishable from the pure damping model result given on page 3.7. 1.55 Hz is used to avoid tank cross waves which occur at 1.6 Hz. The rest of this paragraph has nothing to do with forces on models but is included as one of a number of reader alertness tests. We have the impression that the number of people reading the results is less than the number writing them. If you wish to identify yourself as a reader, please let us know. It would be most interesting to establish the ratio.
Model: D0018 with -3.5 N cm/rad, 4.5 N cm/(rad/sec), -2 N cm/(rad/sec²)

- Surge force: 2 Newton per division
- Heave force: 2 Newton per division
- Mod reference for 1.2 cm wave: .2 radian per division
- Frequency: 1.8 Hz. L/D = 4.82
- Wave amplitude: 0 to 1.6 cm in .2 cm increments.

The vibrations in the 1.6 cm trace were caused by the wave-maker knocking its end-stop and have no significance. The phase shift in surge force might be the result of inaccurate oscilloscope trigger delays which are quite difficult to make at short wave lengths.

Comparisons with other models are given on pages 14.1 and 15.1.
**Surge and Heave Forces on a Medium Beak Duck with Variable Damping**

**Model:** D0018 (see page 19.3)

<table>
<thead>
<tr>
<th>Force</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge force:</td>
<td>1 Newton per division</td>
</tr>
<tr>
<td>Heave force:</td>
<td>1 Newton per division</td>
</tr>
<tr>
<td>Frequency:</td>
<td>1.2 Hz</td>
</tr>
<tr>
<td>Axis depth:</td>
<td>5.5 cm</td>
</tr>
<tr>
<td>Wave amplitude:</td>
<td>0.6 cm</td>
</tr>
<tr>
<td>Damping:</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Undamped</td>
<td></td>
</tr>
<tr>
<td>2.75 N cm/(radian/sec)</td>
<td>half normal</td>
</tr>
<tr>
<td>5.5 N cm/(radian/sec)</td>
<td>normal</td>
</tr>
<tr>
<td>22.0 N cm/(radian/sec)</td>
<td>4 x normal</td>
</tr>
<tr>
<td>Locked duck</td>
<td></td>
</tr>
</tbody>
</table>

We wanted to know how the dynamometer damping setting affected forces on the backbone. In surge, the forces on rigidly held ducks are much the same as normal, but those on undamped ducks are 30% higher. Surge forces are almost indistinguishable with damping set anywhere between half and twice normal settings.

It is rather difficult to set the waterline phase reference for the oscilloscope in the presence of large amounts of reflection which occur with both rigid and undamped ducks. We use a heaving float wave gauge two wavelengths in front of the duck axis. On changing from undamped to normal, the waterline phase at the wave gauge advanced 18°; and from normal to rigid by about 36°. This was corrected for in the photograph.

The phase of surge force advances with damping but only by about 40°. It would be interesting to find wave extraction mechanisms with larger phase differences (say more than 120°) between their forces, but so far we have not been able to find any which do this in surge.

In heave, however, a profound difference is caused by changing the damping settings. There is an almost complete reversal between free and rigid tests. The undamped trace collapses in the wave trough. There is evidence that it is responding at twice the frequency. Compare this with the behaviour of cylinder forces on page 8.5 and 15.1 which also show frequency doubling. The rigid duck has a nice sinusoidal response, and is one of the best behaved heave force curves we have seen. The total phase variation is about 150°.

Experiments with dynamometer negative spring rate variations are given on page 16.1.
There exists a fair amount of experimental data and even more theoretical speculation on the forces on cylinders. A comparison with duck forces should be interesting. While surge forces show a very similar phasing, the heave forces show a large difference. Wave forms are less sinusoidal than for ducks and lower in magnitude. There is close bunching at the top end. It would be very useful to find a shape which has the same magnitude of force as a duck but the opposite phase. One could then interleave shape X with ducks and get some force cancellation.

The high frequency vibrations may be caused by the wave-maker. This is discussed on page 18.1 but see also page 8.2.
SURGE AND HEAVE FORCES ON A CYLINDER AT 1.2 HZ

MODEL: 10 cm CYLINDER

--- Surge force: 2 Newton per division

--- Heave force: 2 Newton per division

Frequency: 1.2 Hz. L/D = 10.8
Axis depth: 5.5 cm
Wave amplitude: 0 to 1.6 cm in .2 cm increments.

We have less of the wave-maker vibrations than in the 1.0 Hz test. Heave forces are small compared with surge. We have stuck to the 2 Newton per division calibration used for the corresponding duck tests.
The vibrations have reappeared but otherwise a boring picture just like the last one. The trend is towards smaller surge forces and larger heave forces as the frequency rises.
SURGE AND HEAVE FORCES ON A CYLINDER AT 1.8 HZ

11/16/67

MODEL: 10 cm CYLINDER

Surge force: 2 Newton per division
Heave force: 2 Newton per division
Frequency: 1.8 Hz
Axis depth: 5.5 Hz
Wave amplitude: 0 to 1.6 cm in .2 cm increments.

There has been a growth in heave forces so that now they equal surge. Comparisons with other modes are shown on page 15.1.
MODEL: 10 cm CYLINDER
Surge force: 1 Newton per division
Frequency: .8 Hz. \( L/D = 24.4 \) \( L'/L = .930 \)
Wave amplitude: 1 cm

Axis depth: 3.0 cm

4.0 cm

4.5 cm

5.0 cm

6.0 cm

There is very little phase variation and no polarity reversal as seen for heave on page 8.4. The positive going rise is linear rather than sinusoidal. There are some sharp positive peaks during the wave trough on all except the 6 cm trace.

A frequency sweep is shown on page 11.1.
MODEL: 10 cm CYLINDER
Surge force: 1 Newton per division
Frequency: 1.0 Hz.  \( L/D = 15.6 \)  \( L'/L = 0.985 \)
Wave amplitude: 1 cm

\begin{itemize}
  \item Axis depth: 3.0 cm
  \item " 4.0 cm
  \item " 4.5 cm
  \item " 5.0 cm
  \item " 6.0 cm
\end{itemize}

There is more variation between traces than at 0.8 Hz, with the shallower settings getting bigger forces. The 6 cm trace is sinusoidal but the high peaks at 200° are abnormal and other tests in very similar conditions do not show them. This test showed the greatest range of inconsistency to the point where we got worried about our calibrations. But on later checking all was found to be in order. Unexpected peaks like this would be very dangerous and must be further investigated. Fortunately, ducks to not seem to show them.
SURGE FORCES ON A CYLINDER AT VARIOUS DEPTHS AND 1.4 Hz

MODEL: 10 cm CYLINDER
Surge force: 1 Newton per division
Frequency: 1.4 Hz L/D = 7.97
Wave amplitude: 1 cm
  _______ Axis depth: 3.0 cm
  ........ " 4.0 cm
  ______ " 4.5 cm
  ----- " 5.0 cm
  .... " 6.0 cm

There is a progressive lead in phase for the 6 cm trace compared with the 1.0 Hz test. The 3 cm trace is much peakier, and the 4 cm traces shows what could be called a spike.

Page 8.8 shows all three tests together with the heave results. Page 8.10 shows some tests down to 8 cm.
HEAVE FORCES ON A CYLINDER AT VARIOUS DEPTHS AND .8 Hz

Frequency: .8 Hz.  L/D = 24.4   L'/D = .930
Wave amplitude: 1 cm

--- Axis depth: 3.0 cm

"  4.0 cm

"  4.5 cm

"  5.0 cm

"  6.0 cm

This shows a demonstration of the interplay of buoyancy and inertia. The 3 and 4 cm trace are almost in phase with water level. Increasing the depth of the model increases inertial effects and reduces buoyancy so that at 6 cm the force in the trough is exactly opposite. There is frequency doubling during the crest for 4.5, 5 and 6 cm depths. There is an obvious conflict of loyalties during the wave crest for 4.5, 5 and 6 cm immersion. Both the 4.5 and 5 cm depth traces show no vestige of upward force.
HEAVE FORCES ON A CYLINDER AT VARIOUS DEPTHS AND 1.0 Hz

MODEL: 10 cm CYLINDER
Frequency: 1.0 Hz. L/D = 15.6 L'/L = 0.985
Wave amplitude: 1 cm

Axis depth: 3.0 cm
4.0 cm
4.5 cm
5.0 cm
6.0 cm

At 3 cm depth the results are the same for the .8 Hz case but at 4 cm inertial forces have taken over in the crest. The 6 cm traces in this group of photographs show rare examples of net upward forces. The long term average at 1.0 Hz is 15 Newton. By comparison, the 5 cm trace shows a downward mean of .5 Newton. Mean force experiments are given on page 17.1.
HEAVE FORCES ON A CYLINDER AT VARIOUS DEPTHS AND 1.4 Hz

MODEL: 10 cm CYLINDER
Frequency: 1.4 Hz.  L/D = 7.97
Wave amplitude: 1 cm

Axis depth:
- 3.0 cm
- 4.0 cm
- 4.5 cm
- 5.0 cm
- 6.0 cm

Buoyancy dominance during the crest for 3 cm depth has now vanished and there is nearly a balance. At 4.5 cm depth the balance occurs during the trough. The 6 cm traces have sorted themselves out. The middle three depths all show an odd jitter between 250° and 290°.
MODEL: 10 cm CYLINDER
Frequency: 1.8 Hz. L/D = 4.82
Wave amplitude: 1 cm

--- Axis depth: 3.0 cm
---- " 4.0 cm
----- " 4.5 cm
------ " 5.0 cm
------- " 6.0 cm

At 3 cm there is strong evidence of excitation at twice wave frequency. During the crest, traces for other depths are all alike with inertia dominant. During the trough, there is a steady trend towards inertia dominance as depth increases. The group of four are shown overleaf.

Corresponding surge experiments are shown on page 8.1.

Amplitude families for the extremes of immersion are on page 10.1.
OVERVIEW OF SURGE AND HEAVE FORCES ON A CYLINDER AT VARIOUS DEPTHS AND FREQUENCIES

MODEL: 10 cm CYLINDER

Heave force: .5 Newton per division
Surge force: 1.0 Newton per division

Axis depth: 3.0 cm
" 4.0 cm
" 4.5 cm
" 5.0 cm
" 6.0 cm

N.B. We have used different force calibrations for heave and surge.

There is broad consistency in the phase of the surge forces which lose their unpleasant spikes once the model is completely submerged. There is not much variation in amplitude but what there is shows a trend of rising with frequency.

The heave forces show some fascinating reversals. They would be an excellent test for any force predicting computer programme. The peak-to-peak forces for the 3 cm trace are falling with frequency, while the deeper forces rise with frequency. To demonstrate that these reversals are not an experimental error we have shown how they vary with amplitude in the tests on pages 10.1 to 10.4.
SURGE FORCES ON A CYLINDER AT VARIOUS DEPTHS AND TWO FREQUENCIES

MODEL: 10 cm CYLINDER
Surge force: 1 Newton per division
Frequencies: 1.0 Hz \( D/L = 15.6 \) and 1.8 Hz \( D/L = 4.82 \)
Wave amplitude: 1 cm

<table>
<thead>
<tr>
<th>Axis depth</th>
<th>Surge force (Newton per division)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0 cm</td>
<td>1</td>
</tr>
<tr>
<td>5.5 cm</td>
<td></td>
</tr>
<tr>
<td>6.0 cm</td>
<td></td>
</tr>
<tr>
<td>7.0 cm</td>
<td></td>
</tr>
<tr>
<td>8.0 cm</td>
<td></td>
</tr>
</tbody>
</table>

Here we are going right down to 8 cm depth, although it would be quite tricky to keep a cylinder stable when completely immersed. If it were the case that exponential decay was the cause of the fall in forces as depth of immersion increases, we would expect that the high frequency test would show a large effect. But the exact opposite happens. The wavelength for the 1.8 Hz test is only 4.8 times the diameter of the cylinder so that in the absence of the model there would have been a 90° phase shift across the space it would have occupied. Some experiments with phase changes caused by the presence of the model would be interesting.

The dangerous spikes have vanished by the time we get to 6 cm deep.
HEAVE FORCES ON A CYLINDER AT TWO EXTREMES OF DEPTH, VARIOUS AMPLITUDES & .8 Hz

MODEL: 10 cm CYLINDER
Heave force: 1 Newton per division
Frequency: .8 Hz  L/D = 24.4  L'/L = .930
Wave amplitude: 0 to 1.2 cm by .2 cm increments
---------------------- Axis depth:  3 cm
----------------------  "    6 cm

N.B. This set only goes up to 1.2 cm amplitude. It was all we could manage at such a low frequency.

At this low frequency the 3 cm trace is really well behaved and the polarity shows that buoyancy is dominant. The 6 cm trace shows reversed behaviour in the wave trough and a conflict in the crest. It is worth tracing the wave forms, though, to see the reversal at higher amplitudes. The comparisons with the next two photographs are interesting.
HEAVE FORCES ON A CYLINDER AT TWO EXTREMES OF DEPTH, VARIOUS AMPLITUDES & 1.0 Hz

MODEL: 10 cm CYLINDER
Heave force: 1 Newton per division
Frequency: 1.0 Hz \( L/D = 15.6 \quad L'/L = .985 \)
Wave amplitude: 0 to 1.6 cm by .2 cm increments.

Axis depth: 3 cm

The 3 cm trace shows greatly reduced forces during the crest in comparison to the trough at this frequency and the crest at .6 Hz. The conflict between buoyancy and inertia at 6 cm has vanished and inertia dominates.

The trough forces at 3 cm depth show the strongest trend towards a square law relationship between force and wave amplitude that we have seen so far. This is in contrast to results during the crest and for the 6 cm depth.
HEAVE FORCES ON A CYLINDER AT TWO EXTREMES OF DEPTH, VARIOUS AMPLITUDES & 1.4 Hz

MODEL: 10 cm CYLINDER

Heave force: 1 Newton per division
Frequency: 1.4 Hz \( L/D = 7.97 \)
Wave amplitude: 0 to 1.6 cm in .2 cm increments.

\[ \text{Axis depth: } \begin{array}{l} 3 \text{ cm} \\ 6 \text{ cm} \end{array} \]

The 3 cm trace is particularly interesting because during the whole of the crest any wave amplitude below 1 cm produces no heave force at all. Inertia and buoyancy are exactly balanced. There is a strong downward force during the trough. Over the three frequencies there is little variation in the magnitude of the downward force during the trough, but a reversal of direction during the crest.

For the 6 cm depth, the upward force during the trough increases steadily with frequency. The ratio of the peaks at .8 and 1.4 Hz show an increase of 84%.

A \( 1/T^2 \) law ought to show a 300% increase. This is one of the few cases where \( 1/T^2 \) pointed in the right direction. Corrections for the exponential decay which use the centre of the cylinder as a reference point are not large enough. All three photographs are shown together for comparison overleaf.
HEAVE FORCES ON A CYLINDER AT 3 cm (----) AND 6 cm (........) AXIS DEPTH FOR VARIOUS WAVE AMPLITUDES AND FREQUENCIES

Tests at fixed wave amplitude and intermediate immersions and frequencies are shown on pages 11.5 to 11.10.
The slopes look rather triangular. The biggest force occurs at 1.2 Hz with a definite reduction on either side. There is much less variation with frequency than in the heave experiments described on pages 11.5 to 11.8. The peaky surge forces in the trough are discussed on page 8.2.
SURGE FORCES ON A CYLINDER AT VARIOUS FREQUENCIES AND AN AXIS DEPTH OF 4.5 cm

SP (1N) C 0.8, 1.0, 1.2, 1.4, 1.8 Hz 4.5 depth 1 amp 2/11.8.76

MODEL: 10 cm CYLINDER
Surge force: 1 Newton per division
Axis depth: 4.5 cm
Wave amplitude: 1 cm

<table>
<thead>
<tr>
<th>Frequency</th>
<th>L/D</th>
<th>L'/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8 Hz</td>
<td>24.4</td>
<td>0.385</td>
</tr>
<tr>
<td>1.0 Hz</td>
<td>15.6</td>
<td>1.000</td>
</tr>
<tr>
<td>1.2 Hz</td>
<td>10.8</td>
<td>1.000</td>
</tr>
<tr>
<td>1.4 Hz</td>
<td>7.97</td>
<td>1.000</td>
</tr>
<tr>
<td>1.8 Hz</td>
<td>4.82</td>
<td>1.000</td>
</tr>
</tbody>
</table>

There is an unusual bulge at 100° for the 0.8 Hz trace. There are still sharp peaks during the trough.
SURGE FORCES ON A CYLINDER AT VARIOUS FREQUENCIES AND AN AXIS DEPTH OF 5 cm

SF (IN) C 0.8, 1.0, 1.2, 1.4, 1.8 Hz 5.0 depth 1 amp 4/21.6.76

MODEL: 10 cm CYLINDER
Surge force: 1 Newton per division
Axis depth: 5.0 cm
Wave amplitude: 1 cm

<table>
<thead>
<tr>
<th>Frequency</th>
<th>L/D = 24.4</th>
<th>L'/L = 0.930</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8 Hz</td>
<td>15.6</td>
<td>0.385</td>
</tr>
<tr>
<td>1.0 Hz</td>
<td>10.8</td>
<td>1.000</td>
</tr>
<tr>
<td>1.2 Hz</td>
<td>7.97</td>
<td>1.000</td>
</tr>
<tr>
<td>1.4 Hz</td>
<td>4.82</td>
<td>1.000</td>
</tr>
</tbody>
</table>

More phase consistency than for the higher depths. The biggest force occurs at 1.0 Hz instead of 1.2 Hz and there is a greater drop towards the high frequency end. The beachward forces during the wave trough are in the ratio of 2.7:1. The exponential decay correction based on axis depth would point to a reduction of 1.6:1 and the 1/T² law would point to an increase of 3.24:1.
SURGE FORCES ON A CYLINDER AT VARIOUS FREQUENCIES AND AN AXIS DEPTH OF 5.5 cm
SF (1N) C .8, 1.0, 1.2, 1.4, 1.8 Hz 5.5 depth 1 amp 2/21.6.76

MODEL: 10 cm CYLINDER
Surge force: 1 Newton per division
Axis depth: 5.5 cm
Wave amplitude: 1 cm

<table>
<thead>
<tr>
<th>Frequency</th>
<th>L/D</th>
<th>L'/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8 Hz</td>
<td>24.4</td>
<td>0.930</td>
</tr>
<tr>
<td>1.0 Hz</td>
<td>15.6</td>
<td>0.385</td>
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<tr>
<td>1.2 Hz</td>
<td>10.8</td>
<td>1.000</td>
</tr>
<tr>
<td>1.4 Hz</td>
<td>7.97</td>
<td>1.000</td>
</tr>
<tr>
<td>1.6 Hz</td>
<td>4.82</td>
<td>1.000</td>
</tr>
</tbody>
</table>

The most consistent of this series of tests with fewer peaks. Only the 0.8 Hz trace shows much distortion. Phase behaviour is close to all the previous tests. The same experiments for heave continue overleaf. There is a combined overview on page 11.9. Amplitude families for this depth are given on page 7.1. A depth sweep is shown on page 8.1.
At the low frequency of 0.8 Hz the heave force is more or less in phase with the water level. We presume that buoyancy forces are in control. But at the higher frequencies there is some very interesting behaviour. There is a strong downward trend and indications of excitation at twice wave frequency. As frequency rises, the downward force during the wave crest is steadily growing and moving backwards in time. During the wave trough the forces are still downward, but as the frequency rises this effect lessens and indeed the forces are nearly upwards at 1.8 Hz.
The trends continue. The perverse behaviour has moved down in frequency and 1.8 Hz shows signs of a sinusoidal response in opposition to the waterline phase. The 1.8 Hz trace shows the only upward force. The large amount of downward force could cause ships to founder. It is odd not to have seen it mentioned more often. Mean forces are discussed on page 17.1.
Heave forces on a cylinder at various frequencies and an axis depth of 5 cm

Model: 10 cm CYLINDER
Heave force: .5 Newton per division
Axis depth: 5.0 cm
Wave amplitude: 1 cm

<table>
<thead>
<tr>
<th>Frequency</th>
<th>L/D</th>
<th>L'/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8 Hz</td>
<td>24.4</td>
<td>0.930</td>
</tr>
<tr>
<td>1.0 Hz</td>
<td>15.6</td>
<td>0.985</td>
</tr>
<tr>
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<td>10.8</td>
<td>1.000</td>
</tr>
<tr>
<td>1.4 Hz</td>
<td>7.97</td>
<td>1.000</td>
</tr>
<tr>
<td>1.8 Hz</td>
<td>4.82</td>
<td>1.000</td>
</tr>
</tbody>
</table>

An astonishing change for the 0.8 Hz in comparison with the previous experiment, and a sinusoidal response for the 1.8 Hz. The 0.8 Hz signal never goes upward at all and the 1.0 Hz signal only just does. There is a tendency towards flatness during the wave trough for all the traces except 1.8 Hz. This is the sort of photograph that makes one think about giving up hydrodynamics in favour of parapsychology.
HEAVE FORCES ON A CYLINDER AT VARIOUS FREQUENCIES AND AN AXIS DEPTH OF 5.5 cm

Heave force: 0.5 Newton per division
Axis depth: 5.0 cm
Wave amplitude: 1 cm

<table>
<thead>
<tr>
<th>Frequency</th>
<th>L/D</th>
<th>L'/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8 Hz</td>
<td>24.4</td>
<td>0.930</td>
</tr>
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<td>15.6</td>
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<td>1.4 Hz</td>
<td>7.97</td>
<td>1.000</td>
</tr>
<tr>
<td>1.8 Hz</td>
<td>4.82</td>
<td>1.000</td>
</tr>
</tbody>
</table>

This continues the trends shown in the previous experiment at 5.0 cm axis depth. Behaviour is unusually simple in the wave trough. Some amplitude families are given on page 7.1.

As there has been some very odd behaviour at 0.8 Hz in the last two photographs, we wondered whether there could have been a problem with the shape of the wave profile. This is considered on page 18.2. There was 15% second harmonic distortion and 3.2% third. We regard this as insufficient to account for the anomalies.
**COMPARISONS BETWEEN HEAVE AND SURGE FORCES ON CYLINDERS WITH FREQUENCY AND AXIS DEPTHS AS VARIATIONS**

**MODEL:** 10 cm CYLINDER  
Heave force: 0.5 Newton per division  
Surge force: 1.0 Newton per division  
Axis depths: 4.0, 4.5, 5.0, 5.5 cm

<table>
<thead>
<tr>
<th>Frequency</th>
<th>L/D</th>
<th>L'/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8 Hz</td>
<td>24.4</td>
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</tr>
<tr>
<td>1.6 Hz</td>
<td>4.82</td>
<td>1.000</td>
</tr>
</tbody>
</table>

**N.B.** We have used different force calibrations for heave and surge.

Heave is variable with depth and frequency. It shows an interplay of buoyancy and inertia forces and can show excitation at twice the wave frequency. Heave forces tend to rise with frequency. Surge is consistent in phase but does not show Morison's magnitude variation with frequency, and indeed it tends to fall. Surge forces are always bigger by roughly 2:1.
FORCE COEFFICIENTS IN SURGE AND HEAVE
FOR A SHORT BEAK AND A MEDIUM BEAK DUCK

DO017
SHORT BEAK
balsa: 6/4 in. 1/4 in. depth
H/D = 12
a) STUPID DYNAMOMETER
damping: 3.5 Ncm/peak

DO018
MEDIUM BEAK
balsa: 8/12 in. 1/4 in. depth
H/D = 12
b) SMART DYNAMOMETER
damping: 5.5 Ncm/peak

C_f vs. L/D

20 14 12 10 9 8 FREQUENCY (HERTZ FOR D=1m)
COMPARISONS BETWEEN HEAVE AND SURGE FORCE FAMILIES WITH AMPLITUDE VARIATIONS WITH AND WITHOUT A SMART DYNAMOMETER: ON A MEDIUM BREAK DUCK

MODEL: D0018
Stupid settings: 0, 5.5 N cm/(radian/sec), 0
Smart settings: -3.5 N cm/rad, 4.5 N cm/(rad/sec), -2 N cm/(rad/sec²)

--- Surge forces: 2 Newton per division
--- Heave forces: 2 Newton per division
--- Nod angle reference for 1.2 cm amplitude wave

Wave amplitudes: 0 by .2 cm to 1.6 cm
Frequencies: .85 to 1.8 Hz as shown
Axis depth: 5.5 cm

Waterline conventions are standard throughout this report. We have water level at its mean position and rising at the start of the trace.

Individual large scale photographs for the smart case start on page 5.1, and those for the stupid case start on page 3.1.

The influence of progressive changes of negative spring with constant wave amplitude on torque, efficiency, instantaneous output power, nod angle, heave and surge forces are shown in photographs on pages 16.3 and 16.4 and in graphs on pages 16.5 and 16.6.

Dynamometer settings were chosen as a compromise between low and high frequency performance with a strong preference for the low end. Careful testing with the Mollison/Hoffman programme has not been done and would be necessary for a final choice.

It is clear that smart power take-off has benefits from the point of view of structural loading as well as improvements in efficiency. It would be an unwelcome complication to backbone design to have to provide different strengths for give/take and hog/sag modes of bending and to have an uneven loading on duck bearings.

As power take-off has such a large effect on backbone forces at the important frequencies we will have to be very careful indeed about the techniques we use in free floating strings.
.85 Hz
L/L = 21.6
L'/_L = .950

.9 Hz
L/D = 19.3
L'/_L = .966

.95 Hz
L/D = 17.3
L'/_L = .977

1.0 Hz
L/D = 15
L'/_L = .985
1.2 HZ
L/D = 10.8

1.4 HZ
L/D = 7.97

1.55 HZ
L/D = 6.50

1.8 HZ
L/D = 4.82
Comparisons between surge and heave forces on cylinders at various immersions
and ducks of varying intelligence and beakiness at .85, 1.0, and 1.4 Hz

Models: 10 cm Cylinder

DC017 Short Beak Duck (see page 19.2)
DC018 Medium Beak Duck (see page 19.3)

Surge force: 2 Newton per division
Heave force: 2 Newton per division

Nod reference for 1.2 cm wave: .2 radian per division

Frequencies: .85 Hz L/D = 21.6
1.0 Hz L/D = 15.6
1.4 Hz L/D = 7.97

Wave amplitude: 0 to 1.6 cm in .2 cm increments.

The cylinder families were taken specially for this series but traces for the ducks appear in large photographs on the pages shown. The heave forces at 4.5 cm depth look rather odd at all frequencies but at .85 they look just like a design for a bra. There is not the slightest pretence at any response at the fundamental frequency. This would be a good shape of ship not to be in.

But considering the wide range of model the phases of the surge forces look consistent and give encouragement about the pipe experiment for bending moment prediction and crest length measurement.

At the bottom two frequencies there is a large difference between heave and surge magnitudes for the medium beak stupid duck and equality of their magnitudes for the smart case. Notice the small nod angle for the stupid medium beak.

At all three frequencies the smart medium beak duck looks very like the stupid short beak. This is reassuring because we thought at first that increasing beakiness to increase the duck's swept area was going to involve penalties in backbone strength requirements.

Some experiments with gradual increases of smartness and the resulting effects on forces angle, torque and efficiency are shown on page 16.1.
THE EFFECTS OF VARYING THE NEGATIVE SPRING COMPONENT OF 
THE DYNAMOMETER TORQUE SIGNAL ON D0018 (see also pp 31-46 in 1st Year Report).

Mollison's analysis of the Hoffman spectra points to the importance of sacrificing high frequency performance in favour of the lower frequencies. In this series we use the medium beaked D0018 and explore the effects of changing the amount of negative spring which helps efficiency at the bottom end of the frequency range.

The dynamometer torque signal which opposes duck movement is derived from the duck's angular velocity. If the torque signal is made proportional to velocity alone we speak of pure damping. But we can also integrate the velocity signal to produce a position signal and include some of it in the torque command. If we choose the polarity of the position signal so that it opposes change in duck position then it would behave like a normal (i.e. positive) spring. The opposite polarity, which tends to lift up ducks which are already high and push down those which are low, is called negative spring. It produces improvements in low frequency performance.

A force taken from a differentiated velocity signal would affect acceleration and could be used to simulate positive or negative inertia. This helps improve performance at high frequencies. Inertia settings on D0018 have little effect at low frequencies. In this set of tests we left inertia at zero and damping at 4.5 Newton cm/(radian/sec). Circuitry is discussed on page 24.14.

The results are shown in the photographs on pages 16.3 and 16.4 and the graphs on pages 16.5 and 16.6. We tested at four frequencies: 0.85, 1.0, 1.2, 1.4 Hz. We used a wave amplitude of 0.6 cm; the biggest which allowed a wide range without torque limiting. We varied negative spring rate from zero to 5 Newton cm/radian in unit steps. The trigger delays used conformed to our standard, i.e. mean water level and rising at time division zero.

The top row of photographs shows surge (———) and heave (………) forces at 1 Newton per division. As the amount of negative spring is increased there is a steady reduction in surge force coupled with a steady increase in heave force. The amount of change is greatest at the lower frequencies. At high frequencies there is less amplitude variation but a tendency towards phase lead for the surge forces. Maximum efficiency tends to occur when surge and heave forces have become similar in magnitude. Perhaps this observation will lead to the understanding of some deep hydrodynamic truth (and perhaps it will not). Ducks with pure damping (see pp 3.1 and 4.1) show unequal heave and surge forces at lower frequencies and similar forces at high frequencies. A balance seems desirable.

The middle row of photographs shows nod angle (………) at 1 radian per division and dynamometer torque (———) at 4 Newton cm per division. The torque motor has to be protected by an automatic current limit and the effects of this can be seen in the test at 0.85 Hz. Negative spring makes very large increases in the demand for torque. For best efficiency we need about 50% extra torque at 1 Hz and more than double at 0.85 Hz. There is also a steady increase in nod angle at 0.85 Hz and a peak in nod angle at the other frequencies. Nod phase lags at all frequencies as negative spring is increased. Neither fact would surprise a dynamicist. Negative spring has very much the same effect as a high centre of gravity. Excessive use complicates recovery from capsize.
The bottom row repeats nod angle (........) and shows instantaneous output power (——) at 25 milliwatt/division. Note that the zero in this row is one division below the centre line of the photographs. With no negative spring the instantaneous output is an offset sinusoid at twice the wave frequency. As negative spring is increased there is a progressive investment of work done by the duck on the water which is shown by the negative power below the zero line. This is part of the price paid for higher efficiency. The optimum setting is about 3 Newton cm/radian and above this efficiency falls and the amount invested seems to grow faster than the return. The benefits of negative spring are less at higher frequencies and indeed at 1.4 Hz it actually makes things worse. This tendency could be reduced by some negative inertia but Hoffman shows that this would be of marginal value.

Conclusions

Negative spring produces:—

- dramatic efficiency increases at low frequencies
- smaller surge forces
- bigger heave forces
- heavy demands on torque
- problems of recovery from capsize.
SURGE FORCE
(- -)
1 N/div
HEAVE FORCE
(.....)
1 N/div

TORQUE
(- -)
4 N cm/div
NOD ANGLE
(.....)
0.1 rad/div

INSTANTANEOUS
POWER (- -)
25 mW/div
NOD ANGLE(-----)
0.1 rad/div

.85 Hz

1.0 Hz
For a medium keel duck:

Wave Amplitude: 0.6 cm

- 0.85 Hz, L/D = 24.41
- 1.0 Hz, L/D = 15.62

Force (Newton):
- Surge Force
- Heave Force
- Nod Angle
- Efficiency

Force (Newton) vs. % Rad:
- Negative Spring N cm/Rad

Graph legend:
- ×: Surge Force
- Δ: Heave Force
- Θ: Nod Angle
- ★: Efficiency
For a medium beam deck:

- Surge force
- Heave force
- Nod angle
- Efficiency

Force Newtons

Wave amplitude: 0.6 cm

1.2 Hz

1.4 Hz
MEAN FORCES ON CYLINDERS AND DUCKS (See also page 23 in First Year Report).

In addition to the alternating forces on floating objects there can be direct forces. Longuet-Higgins and Stewart (5) showed that there should be a horizontal beachward force of

$$\frac{1}{2} \rho g (A \text{incid}^2 + A \text{refl}^2 - A \text{trans}^2) \text{ per unit length of model}$$

where $A$ is wave amplitude, $\rho$ is density and $g$ is acceleration of gravity. This will rise with the square of scale.

Things become more complicated when waves break over the model and we found that with larger waves some ducks have a smaller horizontal force than theory would predict and that cylinders could even move away from the beach. This phenomenon has been explained by Longuet-Higgins in a paper to The Royal Society (6) now in press. We also found that there are much bigger mean vertical forces, sometimes an order of magnitude up on the mean horizontal forces. Some examples are shown on pages 8.4 to 8.7. These are always downward for ducks but can be upward for a deeply immersed cylinder.

In this series of tests we take signals from strain gauges on the model mounting and put them through low pass filters. We tested D0018 at three frequencies and the 10 cm cylinder at three frequencies and three depths of immersion. The results are shown in graphs on pages 17.2 to 17.6.

The mounting is rated for a maximum force of 10 Newton. We are looking for mean forces which are a small fraction of the peak forces involved. We did a drift correction in calm water between each measurement and the figures showed variations of as much as .01 Newton for surge and .02 Newton for heave. We could also get errors from even order non-linearity in the strain gauges. The strain gauge mountings are thin-walled torque tubes with full Wheatstone bridges and ought to be reasonably symmetrical. An asymmetry of 1% would lead to a false offset of about .7% of the alternating force signal. This would be about .03 N for the larger wave sizes.

The theoretical values calculated from wave gauge readings for D0018 agreed well with measured values. We plotted both together at an enlarged scale on the graph on page 17.6. D0018 does not let much water over its back in the wave amplitude available to our present wave-maker.

Conclusions

With sensible design for overload conditions and moderate power limits the mean surge forces will not be a worry. They will amount to less than 1 ton per metre, a comfortable amount to keep mooring ropes from getting tangled. Mean heave forces will require some thought. We measured the vertical spring rate, for two ducks. The results are on page 17.7. A metre width of D0018 would show a rate of about 4 Newton per cm. With mean heave forces of 3 Newton per metre we would expect about .75 cm vertical movement in a free model. This would make a small difference to efficiency. The corresponding model power at this wave amplitude was 1.25 watts per metre, corresponding to 125 kilowatts/metre on a 10 metre full-scale duck.
MEAN SURGE AND HEAVE FORCES ON A CYLINDER AT 3 DEPTHS

MEAN FORCE
Newton

<table>
<thead>
<tr>
<th>3CM DEPTH</th>
<th>HEAVE</th>
<th>SURGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>5CM DEPTH</td>
<td>HEAVE</td>
<td>SURGE</td>
</tr>
<tr>
<td>6CM DEPTH</td>
<td>HEAVE</td>
<td>SURGE</td>
</tr>
</tbody>
</table>

-8HZ
L/D = 24.41

WAVE AMPLITUDE CM

0 2 4 6 8 10 12 14 16 18
MEAN SURGE AND HEAVE FORCES ON A CYLINDER AT 3 DEPTHS

<table>
<thead>
<tr>
<th>Depth</th>
<th>Surge</th>
<th>Heave</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 cm</td>
<td>X</td>
<td>○</td>
</tr>
<tr>
<td>5 cm</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>6 cm</td>
<td>△</td>
<td>△</td>
</tr>
</tbody>
</table>

1.0 Hz
L/D = 15.62

MEAN FORCE
Newton

WAVE AMPLITUDE CM
MEAN SURGE AND HEAVE FORCES ON A CYLINDER AT 3 DEPTHS

MEAN FORCE
Newton:

<table>
<thead>
<tr>
<th>3CM DEPTH</th>
<th>HEAVE</th>
<th>SURGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>5CM DEPTH</td>
<td>HEAVE</td>
<td>SURGE</td>
</tr>
<tr>
<td>6CM DEPTH</td>
<td>HEAVE</td>
<td>SURGE</td>
</tr>
</tbody>
</table>

1.4 Hz
L/D = 7.97

WAVE AMPLITUDE CM
MEAN SURGE AND HEAVE FORCES ON A MEDIUM BEAK DUCK

AT 3 FREQUENCIES AND WITH NEGATIVE SPRING

MEAN FORCE Newtons

<table>
<thead>
<tr>
<th>Frequency</th>
<th>L/D</th>
<th>Symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8 Hz</td>
<td>2.41</td>
<td>O</td>
</tr>
<tr>
<td>1.0 Hz</td>
<td>1.562</td>
<td>0</td>
</tr>
<tr>
<td>1.4 Hz</td>
<td>0.797</td>
<td>0</td>
</tr>
</tbody>
</table>

WAVE AMPLITUDE CM

Dated: 14/07/76
COMPARISON OF MEASURED AND CALCULATED MEAN SURGE FORCE ON A MEDIUM BEAK DUCK

MEAN SURGE FORCE
Newtons

MEASURED MEAN SURGE FORCE, AS ON PITS (S scale x 10)

MEAN SURGE FORCE, CALCULATED FROM FORE-AFT WAVE AMPLITUDE OBSERVATIONS

\[
S_F = \frac{1}{4} \rho g W \left( A_I^2 + A_R^2 - A_T^2 \right)
\]

Using:

\( A_I = \text{WAVE AMPLITUDE INCIDENT} \)
\( A_R = \text{WAVE AMPLITUDE REFLECTED} \)
\( A_T = \text{WAVE AMPLITUDE TRANSMITTED} \)
\( \rho = \text{WATER DENSITY} = 998 \text{ Kg/m}^3 \)
\( g = 981 \text{m/s}^2 \)
\( W = \text{MODEL WIDTH} = 29.5 \text{m} \)

1.4 Hz
L/D = 7.97

DYNAMOMETER

dock: 0.312 crank: 55

DOCK 0.75 0.6 0.75 0.35 0.45 0.2

WAVE AMPLITUDES CM
HEAVE SPRING RATE AND WATERLINE LENGTH

The experiments of page 17.1 showed that waves produce substantial downward forces on ducks. These can only be resisted by buoyancy and so the stability in heave is important.

In these experiments we used ducks with their preferred ballasting (see page 20.1) and progressively lowered them into calm water while noting the change in heave forces on the mounting shown in the photograph on page 17.7.

DO017 is a short beak and DO018 a medium beak duck. Outline drawings are on page 19.1 and 19.2. Both ducks show almost the same heave force line to the point where DO017 is fully submerged. A numerical differentiation of the heave forces yields the heave force spring rate. There is an interesting discontinuity at the working axis depths. Some of the irregularities may have been caused by water entering unfilled ballast holes which we made no attempt to seal.

At the same time we measured the waterline length. This is the horizontal distance from a vertical line through the axis of rotation to the point on the paunch curve where the duck's skin enters the water. This measurement is used in calculating nod spring rate and can be used to fix the orientation of a duck with respect to the water surface. It is measured with an edge-lit graticule clamped against the tank side. Despite careful corrections for parallax errors and meniscus effects the measurements are only accurate to about 1 mm.

Both ducks are .295 metre wide.
HEAVE SPRING RATE AND WATERLINE LENGTH

FOR:
- D007 SHORT BEAK DUCK • • •
- D008 MEDIUM BEAK DUCK ▲ ▲ ▲

HEAVE SPRING RATE
Newton/Cm

HEAVE FORCE
Newton

WATERLINE LENGTH CM

Duck Axis Depth CM
Some experiments, in particular that on page 7.1, showed peculiar high frequency signals. We wanted to find out why. The top trace was made in calm water. We banged the tank side. The resulting frequency is about 55 Hz. This is well above any of the vibrations we have seen and so can be excluded.

The bottom three traces are surge forces when the wave amplitude was 1 cm. They show a consistent pattern from trace to trace rigidly locked to the wave frequency. The ripple frequency is 22.5 Hz. The second trace shows the result of a bang on the wave-maker. It is also at 22.5 Hz. It was transmitted instantly along the tank and so is mechanical rather than hydrodynamical and originates within the wave-maker. It could be cured with more solid foundations.
WAVE QUALITY WITH TEN INCH DIAMETER WAVE-MAKERS

If odd things happen to force signals it could be something to do with bad wave profile. We measured the amounts of second and third harmonic distortion for 1 cm wave amplitudes over the frequency range. The results are shown in Graph 18.5. One would expect a contribution from the trochoidal nature of waves at the 2 Hz end where the height/length ratio is 1:20. The value for .7 Hz makes the ten inch unit useless at that frequency, but at .8 Hz we can just about accept the distortion. It would be possible to get errors from linkage geometry or meter movement non-linearity in the wave gauges but at the wave amplitude of 1 cm we would not expect much. It is possible to add some harmonic correction to the command signal with the circuit discussed on page 24.28.
A DEMONSTRATION OF REPEATABILITY AND RECOVERY FROM TRAUMA

The removal of a concrete plinth from the laboratory resulted in an even layer of concrete dust 2 mm in depth on all horizontal surfaces and forced us to drain the tank and remove every single piece of equipment.

The photographs opposite were taken before and after. Technical details are given on page 3.6.

It may be of interest to note the finely divided concrete dust, 'Expamet' beaches and 'Cimplus' additive are not compatible. After the first reassembly copious quantities of gas appeared on every aluminium object. The p H of the water rose to 10 and an opaque white precipitate formed on the glass sides of the tank. This could only be removed by dilute (1:20) nitric acid. As Expamet and Cimplus had behaved well for eighteen months we concluded that concrete dust was the cause.

In general, duck tests are more repeatable than cylinder tests because a large fraction of the energy has been absorbed. Super beaches and absorbing wave-makers are the secret for stability. Our 10 inch wave-makers are overloaded for a good part of the cycle during the largest waves and so cannot absorb so well. If we include all the photographic processes we can expect accuracy better than 20% for most of the force measurements. Our efficiency calculations are accurate to about 4%.
TUNED BEACHES

For some wave tank experiments the reflections from the beach cause considerable annoyance. An exhaustive experimental study of a large number of beach designs has been carried out by Herbich (7) in preparation for the beaches of the David Taylor Model Basin. A large number of them had reflection coefficients above 10% while the very best ones were less than 5% for their optimum wave lengths. Our own randomly placed, vertical 'Expamet' sheets reflected about 5% at all wave lengths and steepnesses in our test range. Good beaches tend to take up valuable tank space. This note describes a technique which can improve the performance of a beach by about an order of magnitude for one particular test condition in regular waves.

Whatever design of beach is used, its reflection will form a partial standing wave. The first step is to find a node. An object placed in the tank at a node will cause a reflection in antiphase to that from the beach. If the magnitude of this reflection is close to that of the beach reflection, then there will be a large reduction in the total reflection. The most convenient object is a pair of overlapping vertical plates reaching down to the tank bottom. The amount of overlap can be adjusted to change the amount of reflection. It will be found that the correct phase of reflection occurs with the reflector placed a short distance on the beachward side of the node. This distance seems to be a little less than the width of the reflector. It is not clear to us whether this is because the reflections are really occurring from the front of an imaginary enclosing cylinder or because the reduction in standing wave ratio changes the wavelength by a small amount or because of a change in conditions at the main beach.

It is unfortunate that the reflection from a sloped beach depends on wave amplitude as well as frequency so that two adjustments to the secondary reflector are necessary. It would be best to use a secondary reflector with the same sort of amplitude dependence as the beach. Vertical wave absorbers and reflectors are alike and require only a frequency adjustment. It is also unfortunate that tuned performance at one wave length inevitably spoils performance at half that wave length. A question: where does the energy go?

Reflection coefficients for various widths of reflector are shown in the graph below. The reflection coefficient is nearly the square of the occlusion coefficient.
DUCK TYPES

symmetrical exponential

D0016 - D0017

D0018

arcs & tangent, flat back

D0011 - D0015

DYNAMOMETER TUBE

(displaced in D0014)

1375 in

5 cm

7.5 cm

13
D0016 18/2/76
D0017 10/5/76

SHORT BEAK DUCK

Weight without dynamometer or ballast
D0016: 1159 g
D0017: 1020 g

\[ R = r \frac{2a}{\pi} \]

\( \approx 0.0196 \) centimetres

Dimensions in centimetres

105° between start of curves

G centre of gravity of D0017 with ballast 234.234.0 in tubes 1-3" returning
D0018 MEDIUM BEAK DUCK

weight without dynamos or ballast 1226 grams

$R = re^{\frac{2A}{a}}$

$= 5 \frac{2A}{100} \text{ centimetres}$

tubes for 1/2" dia. ballast rods

85° between starts of curves

center of gravity with ballast 0.156, 0.312, 0.234, 0.156 in tubes 1-6 respectively

dimensions, in centimetres.
DRY MEASUREMENTS

We are interested in the values of the moment of inertia and the position of the centre of gravity of various ducks. The models are ballasted as for normal use but held hanging down from their bearings like a pendulum. We apply a slow (.159 Hz) sinusoidal torque signal $\tau$ and measure the resulting angular movement $\theta$. This frequency is well below resonance and the response is not affected by frequency changes. It is necessary to superimpose a dither signal at 30 Hz to reduce bearing stiction. We get the value of nod stiffness $\tau/\theta$ for the duck as a pendulum in air. The distance $R$ of the centre of gravity from the axis of which is given by $R = \tau/\theta M g$. Mass $M$ is measured without dynamometer motors which we count as part of the backbone.

Next we invert the normal velocity damping signal to give negative damping, but pass it through a severe limiter. The square pulses of torque are supplying just enough energy to make up for bearing friction. This makes the duck swing with steady amplitude at its natural frequency $F$. This is very consistent. We can then calculate the dry inertia from

$$I = \frac{\tau}{\theta^2 4\pi^2 F^2}$$

When the duck is hanging in air we note the point along the paunch curve which is beneath the axis of rotation. This allows us to define the line on which the centre of gravity lies. The positions are marked on the duck drawings on pages 19.2 and 19.3.

DO017 was intended to be a copy of DO016 which had an unfortunate accident caused by an over-heating torque motor.

DO018 was designed after our first tests in Pierson-Moskowitz spectra when it looked as if a bigger beak was needed to cope with bigger waves. It requires more torque than DO017. We hope to try an increase of beak length and to fit the next range with more powerful torque motors giving about 150 N cm per metre length of model. Torque density rises with the cube of scale.

Results are tabulated as follows:

<table>
<thead>
<tr>
<th></th>
<th>mass Kg</th>
<th>Air stiffness Nm/rad</th>
<th>C.G. radius M</th>
<th>F. Nat. Hz</th>
<th>Dry Inertia Kg m^2 x 10^-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>DO016</td>
<td>1.479</td>
<td>.42</td>
<td>.029</td>
<td>1.45</td>
<td>5.1</td>
</tr>
<tr>
<td>DO017</td>
<td>1.503</td>
<td>.46</td>
<td>.031</td>
<td>1.46</td>
<td>5.5</td>
</tr>
<tr>
<td>DO018</td>
<td>2.110</td>
<td>.77</td>
<td>.037</td>
<td>1.55</td>
<td>8.1</td>
</tr>
<tr>
<td>DO019</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DO020</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DO021</td>
<td></td>
<td></td>
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<td>DO022</td>
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<td>DO023</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DO024</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>DO025</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A NOTE ON SCALE

If dynamic similarity exists between model and prototype, we can get full-scale figures from model figures with the right scaling factor. This is best described by some index of scale.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Index of scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave height and length</td>
<td>1</td>
</tr>
<tr>
<td>Period</td>
<td>.5</td>
</tr>
<tr>
<td>Frequency</td>
<td>-.5</td>
</tr>
<tr>
<td>Nod angle</td>
<td>0</td>
</tr>
<tr>
<td>Angular velocity</td>
<td>.5</td>
</tr>
<tr>
<td>Angular acceleration</td>
<td>-1</td>
</tr>
<tr>
<td>Buoyancy</td>
<td>3</td>
</tr>
<tr>
<td>Inertial forces</td>
<td>3</td>
</tr>
<tr>
<td>Velocity forces</td>
<td>3</td>
</tr>
<tr>
<td>Drift forces</td>
<td>3</td>
</tr>
<tr>
<td>Torque</td>
<td>4</td>
</tr>
<tr>
<td>Power</td>
<td>3.5</td>
</tr>
<tr>
<td>Power per unit length</td>
<td>2.5</td>
</tr>
<tr>
<td>Force per unit length</td>
<td>2</td>
</tr>
<tr>
<td>Torque per unit length</td>
<td>3</td>
</tr>
<tr>
<td>Mass</td>
<td>3</td>
</tr>
<tr>
<td>Inertia per unit length</td>
<td>4</td>
</tr>
<tr>
<td>Buoyancy spring per unit length</td>
<td>3</td>
</tr>
<tr>
<td>Damping per unit length</td>
<td>3.5</td>
</tr>
<tr>
<td>Heave and surge distances</td>
<td>1</td>
</tr>
<tr>
<td>Heave and surge velocities</td>
<td>.5</td>
</tr>
<tr>
<td>Heave and surge accelerations</td>
<td>0</td>
</tr>
</tbody>
</table>

The ratio of wavelength to diameter L/D is the most useful indicator of dynamic similarity. The ratio of wave height to diameter should also be considered. Scale effects should be less of a worry for inertia dominated wave behaviour than in other fields.
In addition to the obvious inertia of concrete and the less obvious modifications from active hydraulics, there is a contribution of inertia from the water around the duck. Knowledge of its value is necessary in the prediction of the natural nodding frequency. Wave theoreticians inform us that it is frequency dependent. If it turned out that there was an increase with fall in frequency, then the band of resonance could be made wider. This would be a good thing.

In these experiments we measured the real and imaginary components of angular velocity in response to a sinusoidal torque at a number of frequencies. The model was trimmed and ballasted but the dynamometer was not used. An anti-stiction dither signal at 30 Hz was superimposed. Two hundred sheets of 'expamet' were used as a beach on the beak side, with one hundred sheets astern. We found it necessary to use a tapering packing density to get the very least reflection.

Results for torque amplitudes of .01 and .03 Newton Metres and frequencies from .7 to 3 Hz are shown in Graph 27 on page 21.2. Very fine plotting would show some re-entrant loops reminiscent of those in Graph 11. We believe that these may be a feature of tank reflection, because rearranging the beach often disturbs them.

If velocity is measured in terms of \( (a + jb) \) the stiffness is \( S \), and \( \omega = 2\pi \times \text{frequency} \), the total inertia is

\[
I_{\text{total}} = \frac{1}{\omega} \left( \frac{S}{\omega} - \frac{b}{\omega^2 + b^2} \right)
\]

This assumes that we blame all the frequency dependent anomalies on inertia. There is no way of distinguishing added virtual inertia from subtracted virtual buoyancy. Perhaps we should talk only of reactance.

At very low frequencies the apparent wet stiffness of D0016 was .57 NM/rad. Its hub depth was .052 metres and its waterline length forward of the vertical through the hub is .077 metres.

On the constant spring assumption, \( I_{\text{total}} \) is plotted in Graph 28 on page 21.3. It shows a splendid increase at low frequencies. The preferred setting for D0016 damping is .025 NM sec/rad. This corresponds to the maximum value along the real axis and supports ideas of matching impedance. Added inertia of ships increases in shallow water. A quick efficiency test shows some improvement at frequencies of .8 and .9 Hz, with a false bottom at .3 M below the surface. Normal depth of water is .6 M.

D0016 is .297 metres wide. The hungry naval architect's guess of

\[
\frac{1}{32} \pi \int L^4 = 1.026 \times 10^{-3} \text{ kg m}^2 / \text{M}
\]

for added inertia is only good for the high frequency value.

Graph 29 (on page 21.4) shows the circular plot, calculated for a well-behaved mass spring dash-pot with Inertia = .01 kgm², Stiffness = .57 NM/rad and damping = .025 NM sec/rad. It is worth comparing this with Graph 27. Added inertia for a duck has been calculated by Katory (11).
27: VELOCITY VECTOR DIAGRAM

for DUCK DRIVEN IN NOD

at FREQUENCIES from 7-30 Hz
and at 2 drive torques.
Total Inertia in Nod

\[ \text{Kg m}^2 (\equiv \text{Nm s}^2) \]

28: Duck Inertia in Nod Against Frequency

\[ I_{\text{tot}} = \frac{1}{w} \left( \frac{S}{w} - \frac{bT^2}{a^2 + b^2} \right) \]

- \( S \): Spring rate (inertial) = 570 Nm/rad
- \( a + b \): The real and imaginary component of velocity
- \( T \): Amplitude of applied force

- O1 Nm
- X 0.3 Nm

\[ \frac{1}{\sqrt{2}} Te'L^2 \]

'dry' Inertia (0.506 Kg.m²)

Detail: \( L = 52 \text{ cm} \)
VELOCITY VECTOR DIAGRAM

for HYPOTHETICAL SIMPLIFIED DUCK IN NOD

Velocity for FREQUENCIES shown calculated using:

\[ \frac{TR}{a} = \frac{R^2 + X^2}{R^2 + X^2} \]

\[ j \cdot \frac{TX}{R^2 + X^2} \]

These values chosen for some spring rate as real duck, and to give resonance at some frequency.

Duck would behave like this if there were no frequency dependent added inertia.
MORE TORQUE LIMIT EXPERIMENTS INTRODUCING THE HUNCH-BACKED DUCK

(This note extends the work of Graph 13 in the 1st Year Report.)

The capital cost of the front end of the electro-hydraulic system will depend on the peak forces it is required to exert on the duck. We are interested in optimising the amount of installed hydraulic capacity and in calculating the losses associated with understrength systems. The data gathered will form the basis of a more sophisticated power limit prediction than that used in Mollison's first paper. (3)

Graph 26(a) on page 22.2 shows the shape of efficiency curves at a fixed wave height, and contains the ballasting and dynamometer settings. The rest of the graphs are more complicated.

We suggest that the reader first studies a graph from the middle of the frequency range, say 26(d) on page 22.6 at 1.4 Hz, where behaviour is more intelligible. There are three different sorts of line. They are for each frequency;

(1) Efficiency against wave amplitude for torque limits of 10, 4, 2 and 1 N cm. These curves always fall with increasing wave amplitude except for very low wave frequencies, where stiction may be playing a significant part.

(2) Mod amplitude against wave amplitude for each of the same torque limits. These curves always rise and they diverge to rise faster for low torque limits.

(3) Percentage of power transmitted behind the duck. This is shown only for the torque limits of 10 and 2 N cm.

These curves are for D0016 which is the first of the hunch-backed ducks. Its paunch is designed for wavelength = 10 diameter, i.e. Frequency = 1.25 Hz. A reduction in buoyancy spring rate is of benefit in giving low Q and so widening the bandwidth. It can be achieved by raising the duck's centre of gravity. The limit to this is the requirement that there should be spontaneous recovery from the capsized position unassisted by use of the hydraulic systems. We have changed the back shape so that the restoring buoyancy rises more rapidly after overload. The price is shown by the increase in percentage of power lost in the wave generated astern. In the case of D0016 the back shape is a mirror image of the paunch.

If its ballast could be shifted by pumping between chambers, then it would be quite content to work with waves from the rear. If Budal and Falnes(8) are correct, we might be able to widen thin ducks and use alternate ducks in the reversed mode when there was sufficient energy from behind.

Values for the ratio of torque supplied against that which would have been required without the limit are shown in various places. Full-scale power is shown at the top of the graphs for scales of 100 and 140. D0016 is .297 m wide. We plan to fit D0019 with a new torque motor giving 50 N cm of torque. (See page 24.16 for torque limit circuitry.)
26 **TORQUE LIMITS**

(a) **EFFICIENCY/FREQUENCY**

for 4 DIFFERENT TORQUE LIMITS

WAVE AMPLITUDE/BUCK DIAMETER = 08

<table>
<thead>
<tr>
<th>BALLAST</th>
<th>AUS DEPTH</th>
<th>DYNAMOMETER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>15°</td>
<td>15°</td>
<td>5</td>
</tr>
<tr>
<td>0</td>
<td>3</td>
<td>-25</td>
</tr>
<tr>
<td>25</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

**DOCK (SHORT BEAK) 15$^\circ$, 15$^\circ$, 0, 3 cm, -25, 25, 40**
PERCENT OF INCIDENT POWER

Θ (ANGULAR DISPLACEMENT)
RADIANS AMPLITUDE

26 TORQUE LIMITS:
EFFICIENCY, TRANSMITTED POWER,
AND NOSE ANGLE AGAINST WAVE AMPLITUDE

b) 10Hz \( \frac{L}{D} = 15.39 \)
for different values of TORQUE LIMIT

TORQUE LIMIT VALUES are in Newton cm

SPOT VALUES (\( \Delta \)) near efficiency points (\( \circ \))
are actual torque/torque that would occur without limit

WAVE AMPLITUDE / DUCK DIAMETER
26. Torque Limits: Efficiency, Transmitted Power and Node Angle Against Wave Amplitude for different values of Torque Limit.

Torque Limit Values are in Newton cm.

- Efficiency @ TL = ±10
- Efficiency @ TL = ±5
- Efficiency @ TL = ±2.5

θ (Angular Displacement) in radians amplitude.

% Transmitted @ TL = ±2
% Transmitted @ TL = ±10

Wave Amplitude vs. Duck Diameter.

Spot values (4 points) show efficiency drops due to actual torque/torque that would occur without limit.

Incident Power Percent: 90, 80.
PERCENT 90 OF INCIDENT POWER

26 TORQUE LIMITS: EFFICIENCY, TRANSMITTED POWER AND NOD ANGLE AGAINST WAVE AMPLITUDE

d) $1.442 \cdot 10^6 = 797$

for different values of TORQUE LIMIT

TORQUE LIMIT VALUES are in NEWTON cm

\[ \Theta \] (angular displacement) in RADIANS AMPLITUDE

\% TRANSMITTED @ TL = \pm 2

\% TRANSMITTED @ TL = \pm 10

WAVE AMPLITUDE/DUCK DIAMETER
26 Torque Limits: Efficiency Transmitted

Power vs. Node Angle Against Wave Amplitude

For different values of Torque Limit

Torque Limit Values are in Newton cm

Percent of Incident Power
Efficiency Curves
Plotted against wavelength/model diameter

C) DO017: Short Beak Duck
With and without a SMART Dynamometer

[Configuration details]

STUPID: Damping = 3.5 Nm/ rad/s
SMART: Spring = -2.5 Nm/ rad
Damping = 3.0 Nm/ rad/s
Inertia = -2.0 Nm/ rad/s²

DO017: 3/4 0 55cm

FREQUENCY (Hz D=1m)
NARROW TEST TANK ELECTRONICS SCHEMA

This diagram gives a bird's eye view of the parts and interconnections used while testing ducks in our narrow tank. The photograph on page 26.5 shows the operator's test bench on which all the units from the third row down are situated. Rows 1 and 2 are on and beside the tank.

The main telephone exchange in the system is the Oxley Matrix Pinboard. It can route any parameter to any measuring instrument but we have tried not to include it in any feedback loops, all of which occur above it in the diagram.

Feedback loops occur wherever we are using electronics not merely to measure but also to control parameters. These are used in the duck, the Surge-Heave Pitch Rig and the wave-maker. (See 'Dynamic System Control' on page 24.15.)

We have used large numbers of analogue meters, putting one on nearly every interesting parameter. This provides an instant check that everything is working and that nothing is over-loading as well as giving a measurement.

Circuit diagrams are included for most of the boxes in the schematic.

Note on Box Labels

P.A.: power amplifier.
S.H.P.: Surge-Heave Pitch Rig. (See page 24.14)
Calculus Box: uses velocity to compute acceleration and displacement (See page 24.14)
Dynabox: controls feedback to P.A. (See page 24.14)
M.P.X.: Multiplexer
H²T: see 24.22 - Wave power measurement in a narrow tank.
WAVE HEIGHT MEASUREMENT TECHNIQUES

The instrumentation of wave height can be done in many ways. Most techniques have their advantages and their disadvantages, which means that what may be near perfect in one situation may be totally unsuitable elsewhere. We have developed three ways of measuring waves, and are looking into others.

All wave tanks have several frequencies which excite lateral waves. Our worst is 1.6 Hz, where the wave length is exactly double the tank width. However, even at other frequencies an amount of sideways wave is present and single point measurements across the tank show variations in height. This means that a point wave height gauge, such as a resistive wire or capacitive gauge, can give a wrong impression of the total wave hitting a device, unless many readings are taken.

On the other hand, a heaving float gauge across the whole width of the tank while giving a better idea of the average wave height (it should ideally be RMS) tends to attenuate the wave passing it and insert a phase shift. This is particularly true at high frequencies, where the amplitude response of a float becomes suspect as well.

Neither of these techniques is direction sensitive in any way, and it is important to be able to discriminate between transmitted and reflected waves for efficiency calculations. In a single frequency wave, it is relatively easy to find a point along the tank of maximum response (an antinode) and minimum (a node). The average of the two readings cancels the reflected wave and gives the transmitted wave only. Since the node and antinode are separated by one quarter wavelength, it is possible to put two gauges this distance apart and take their average electronically. Even if they are not on the node and antinode, this reading is acceptably accurate unless the reflected wave is large.

In a mixed spectrum where there may be reflections at several frequencies, a new approach is called for. If we could plot the path of water particles just under the surface, some computation would give us the height of the transmitted wave at any frequency. Another technique would be to measure the wave height at several different distances down the tank and compute each frequency separately using the single frequency technique. We are investigating these approaches.

The practical problems of realising the possible performance of the gauges we have made are discussed in the specific descriptions.
HEAVING FLOAT WAVE GAUGE

Preamble

This is the first and so far the most reliable gauge we have made. It comprises a cylindrical float, 11 inches wide and 1.25 inches in diameter. It is held by a linkage which constrains it to move in a vertical line. Both cylinder and linkage are made of rolled paper. The float is waterproofed with polyurethane while the linkage is impregnated with epoxy resin. It drives two velocity transducers (50 microammeter movements). The photograph on page 26.8 shows construction details. They should present no difficulties to the competent amateur aeromodeller.

Circuit Description

The left and right hand meter outputs are respectively buffered and amplified by op amps 1 and 2. Their outputs are summed at op amp 3, and op amp 4 calibrates the velocity output before sending it from the gauge back to the bench. Op amp 5 integrates the velocity to give a displacement signal, calibrated by op amp 6, which is available at the gauge itself. It is 1 volt per centimetre.

On the bench, op amp 7 gives a gain, switchable to match the scale on a 1, 3, 10 meter. This amplified signal is integrated by op amp 8 to give the final height signal. The last three op amps, 9, 10 and 11, demodulate the varying water level signal and present it, calibrated as the amplitude of a sine wave, as a steady level to be read on a meter.

The demodulator circuit senses the mean rather than the RMS values but most of the signals are pure enough for this not to matter. Harmonic content can be measured using the transfer function analyser.
HEAVING FLOAT WAVE HEIGHT GAUGE

SI - Increases sensitivity for small waves
METER R & L - Meter movements left and right used as velocity sensor.

Top 2 lines of op amps are on gauge mechanism, rest on bench.

* Select 15 to 100%.

Power ±15V, ±7.5V, 0V

D.C. Jeffrey 13:8:76
TWO-WIRE RESISTIVE WAVE GAUGE

To use this gauge as an accurate wave height instrument requires frequent calibration since it measures height multiplied by water conductivity and the latter varies nearly as much as the former. The gauge is useful, however, as a phase instrument and it shows the shape of the wave passing it accurately. The problems of meniscus have been largely overcome by using a very fine wire (38 gauge) and leaving it immersed when not in use. It seems to develop a coating of slime which keeps it permanently wet. Steel wires seem much better than phosphor bronze; perhaps they have less effective anti-fouling. We are currently developing a three-wire gauge which promises to get round the calibration drift problem.

Circuit Description

Op amp 1 establishes a reference voltage (of about 10 volts) and using this op amps 2 and 3 make a precise amplitude 3KHz square wave oscillator. This is fed via the calibration pot to op amp 4 which filters out the higher harmonics leaving an impure sinewave to be fed to op amps 5 and 6 and with their help wire no. 1. The null pot is for the output of op amp 6, which should ignore the alternating voltage on its input as long as wire 1 is open circuit. Any current flowing into or from wire 1 must be supplied via the 1K feedback resistor on op amp 6; therefore the voltage at its output is a measure of the wire current. This is proportional to the water conductance multiplied by the depth of immersion.

Op amp 7 supplies wire 2 with exactly the opposite voltage to wire 1 and this means that the nett current flow into the tank water is zero.

For a linear height response, it is important to keep the output impedance feeding wires 1 and 2 as small as possible. It is obvious that wire 2 is fed in this way, but less so in the case of wire 1. In fact the impedance of the circuit at its output was measured to be 0.1 ohm.

The output from op amp 6 is a 3KHz carrier, amplitude modulated by the wave signal. This is demodulated by op amps 8 to 12 and the offset voltage present because of the depth of immersion of the wires is removed by A.C. coupling into op amp 13.
2 WIRE RESISTIVE WAVE HEIGHT GAUGE

nullpot - zeros H with wires out of water

* = Selected to 0.1%
QUADRILATERAL LINKAGE WAVE GAUGE

So far this gauge has not been necessary for our experiments and its performance has not been fully assessed, but we will need it to measure transmitted power in a mixed sea. It consists of a T-shaped float, whose vertical member is totally submerged. It is as loosely held as possible on a very light balsa wood quadrilateral linkage which permits it three degrees of freedom—pitch, surge and heave. Meter movement velocity transducers are connected to the linkage and the surge and heave velocities computed—these are integrated using the same electronics as two of the heaving float gauges, to give signals corresponding to the horizontal and vertical movement of the float. So long as its width and depth are small compared with a full wavelength, it should faithfully reflect the natural movement of the water particles.

To date, we have used it for showing on an oscilloscope the difference between particle movement in a travelling wave and a standing wave. A photograph of the instrument appears on page 26.12.

Circuit Description

The two velocity transducers are buffered and amplified by op amps 1 and 4. Because of the linkage geometry, surge and heave are each coupled to both transducers in such a way that surge = the sum and heave = the difference between their outputs. Summing is done at op amp 2, while 3 calibrates surge velocity; op amp 5 takes the difference and this is calibrated by 6 for heave.

The two velocity signals are taken back to the bench and integrated by the circuitry for heaving float gauges A and B respectively to give calibrated displacement signals.
QUADRILATERAL WAVE HEIGHT GAUGE

METERS 1 & 2 - METER MOVEMENTS USED AS VELOCITY TRANSUDERS

* = SELECTED TO .1%  
POWER SUPPLIES ±15V, ON

D.C. JEFFREY 23RD
TRANSODER CONDITIONING AMPLIFIERS

Strain Gauge Conditioning Amplifiers

Our philosophy when using strain gauges is to position the amplifier as close as possible to the gauge itself, sending out power lines and getting back a conditioned ground referenced signal. To reduce the number of wires we hang the gauges between +2 volts and ground, which means that the op amp inputs are at +1 volt. The 300 ohm resistor from ground to -5 volts passes the gauge current "through" ground to avoid nasty offset voltages developing. We use a four element gauge on all occasions.

The main limitation to the resolution of strain gauges at steady, as opposed to alternating, strains is to be found in temperature dependent drifts. A larger current through the gauge gives a larger signal but if the gauge becomes warm, draughts can seriously affect its performance. The technique we have adopted is to run the gauges in a draught-excluding shroud at a comparatively low current (17 ma) and concentrate on the electronics. We found the LM 725 op amp well suited for the amplifier, particularly if it is run at a low voltage to avoid self-heating. We supply it with + and - 5 volts. Since we are dealing with low impedances, the critical parameter is not offset current but offset voltage, which is nominally .6 microvolt per degree Centigrade. Under these conditions, thermal drift in the strain gauges is still the main source of error but stability is such that we can expect drifts of about a quarter of a microstrain per hour. Since our full-scale signal is a thousand microstrain, this is acceptable.

Another source of error in the circuit we are using is intrinsic in a bridge configuration. It is very small, however; half a part per thousand for a full scale signal and less at smaller strains.

Velocity Conditioning Amplifier

We use the RS components 50 microamp miniature edge meter as an angular velocity transducer in several applications. With its cover removed it is easily mounted and a simple glue coupling to its needle is all that is necessary to drive it. Its resistance is 1.2 kilohms and its output approximately 45 millivolts per radian per second.

Since the velocity signal is usually integrated to give a displacement signal, it is very important not to have an appreciable temperature dependence in the offset voltage. We again use the LM 725 op amp as close to the meter as possible.

A final note - the LM 725 needs to have its offsets nulled externally for best performance. Rather than using a preset pot which is comparatively expensive and not very reliable, we adopted the following technique. Although there are two pins supplied for offset adjustment, it will be found that only one is needed. Which it is depends on the op amp. A switchable resistance box is connected between this pin and +5 volts, and adjusted until a null is obtained; then the single resistor (or occasionally the pair) that most closely matches the value in the resistance box is soldered permanently in.

The photograph of the SHP rig on page 26.15 shows two velocity transducing meters at work.
STRAIN GAUGE CONDITIONING AMPLIFIER.

CONDITIONING AMPLIFIER USED WITH SG/AMP METER MOVEMENTS USED AS VELOCITY TRANSDUCERS.

NOTE - LM 725 OP AMPS USE ONLY ±5V FOR LOW SELF HEATING.

IN SG AMP, 300.5Ω TO -5V SINKS SG CURRENT! NO GROUND CURRENT. OFFSETS NULLED WITH FIXED Rs.(SOT)

POWER SUPPLIED ±5V, ±2V, 0V

D C JEFFREY 4.8.76
POWER AMPLIFIER

Preamble

All of the signals we send to motors are pure forcing functions. The torque to the duck, heave and surge drives to the S.H.P. rig and wave-maker drive should all be velocity independent, i.e. undamped. Controlled amounts of damping are added elsewhere. Since the torque supplied by an electric motor is proportional to the current driving it, we are obliged to use current output amplifiers.

Circuit Description

The main amplifying element is op amp 1. (The power section has a voltage gain of four but a high current capacity.) Op amp 1 drives TR3 directly and TR2 via the biasing TR1. The TRs2 and 3 drive the output Darlington DT1 and DT2, which deliver current I OUT into the load. This current passes through Ro in series with the load and the voltage drop across Ro is fed back through a resistor network to the inverting input of op amp 1, thus completing the feedback path.

Current limiting is done in two ways. Both use the voltage drops across RF1 or RF2 as a measure of the current in either half of the output stage.

TR6 or 9 is turned on when this voltage reaches about 1 volt and it then supplies the collector current for TR2 or 3, stopping any increase in the Darlington base drive.

Pairs of transistors TRs4 and 6 and TRs 5 and 7 behave in a similar fashion, diverting current from the Darlington bases. However, their turn-on time is delayed by the RC 22 K and 100 microfarad and the RF voltage at which they start operating is .6V.

It can be seen that in this way a prolonged overdrive condition results in the voltage across RF starting at 1v but dropping to .6v after a few seconds. This allows a motor to be driven to its peak instantaneous torque but prevents it staying there and overheating.

Op amp 2 is an overload warning device. It monitors the inverting input voltage on op amp 1, which should be a virtual earth point. It only leaves earth potential when the feedback current cannot match the input current and this will only happen if there is voltage or current limiting at the output stage. It drives a L.E.D. warning light.

Op amp 3 gives an output which is identical to the input signal, except that it gives a true picture of the output current in the presence of limiting.
POWER AMPLIFIER WITH CURRENT OUTPUT

\[ I_{\text{max}} = 10A \]

LED OVERLOAD INDICATION. SEPARATE INST. AND LONG TERM LIMITS.

* RC CHOSEN TO STABILISE AMP. FOR LOAD.

POWER SUPPLIES \( \pm 15V, \pm 30V, 0V \)

DC JEFFERY 3-8-76
GENERAL DYNAMICS CONTROL CIRCUIT

Preamble

Mechanical motion of an object can be opposed (or assisted) by three important forces:

1. A force whose magnitude is a function of its displacement. A spring is a familiar form of this.
2. A force whose magnitude is a function of its velocity. This is a damping force.
3. A force whose magnitude is a function of its acceleration.

Of these forces, (2) is the only one which lets us extract energy from a system. (1) and (3) simply store energy from one part of the cycle and give it up at another.

We have found experimentally that a duck needs its angular motion opposed by amounts of all three forces for efficient operation over a bandwidth adequate for real sea conditions. This is also true of the wave-maker (which absorbs as well as making waves) and the ability to apply these forces to oppose or assist movement of the S.H.P. rig is one way to try to model real backbone behaviour.

This circuit computes these forces and enables us to vary them in amplitude and polarity.

Circuit Description

The input to the circuit is a velocity signal. In the case of the wave-maker this is from a tachogenerator, while the duck uses a torque motor in dynamo mode. The S.H.P. rig uses 50 microamp meter movements whose needles are mechanically connected to the heave and surge axes. This last technique is cheap and gives a clean signal. The velocity signal is conditioned to a reasonable voltage level (near its source). See S.H.P. rig photograph on page 26.1.

The integrator turns the velocity signal into a displacement signal, calibrated in some convenient units. With an integrator of this sort, offset voltage gives the dominant drift and it is likely that the velocity preamplifier is its greatest source. (A larger C and smaller R will always reduce the effect of bias current.) In our system there is no advantage in using a better op amp than the CA 3130. It is usually desirable to have a leak resistor across an integrator. Our RC is chosen to give $1^\circ$ phase error at about 1 Hz.

The amplifier before the differentiator simply calibrates the velocity signal.

The differentiator turns the velocity signal into an acceleration signal, again conveniently calibrated. The integrator in the feedback path acts as a slew rate limiter to avoid excessive high frequency noise getting through. At high frequencies the gain stops rising; the RC controlling the corner frequency is chosen to give $1^\circ$ phase error at about 2.5 Hz.

The three signals, displacement, velocity and acceleration, each pass through an attenuator, a polarity switch and gain switch to a summing junction. This summed signal is taken through a power amplifier and used to drive a torque motor which is coupled to the motion whose velocity was originally measured. This section is referred to as the Dynabox. It is used to load D0018 in the photograph on page 26.2 and supplies the negative spring on page 16.1.
Dynamic System Control (as used in S.H.R. Dynabox)

Power 15V, ±5V

This system is used to control spring rate, damping and inertia in heave and surge.

Similar systems are used in deck and wingmaker nod.

D.C. Jeffrey 22-7-76
SWITCHABLE CHANGES TO DYNABOX CHARACTERISTICS

Preamble

The duck's angular acceleration, velocity and displacement are fed to the dynabox and using them it computes the torque signal to feed back to the duck. Normally, all that happens is the summing of these three signals (with possible inversion) in different amounts, but in addition there are the following non-linear changes which we can switch into the circuit:

(1) A torque limit. This not only limits the total torque signal going to the duck, but can also vary the negative limit independent of the positive. Experiments using torque limits are reported in Section 22.

(2) A separate gain for each torque signal polarity. This can be used to take all the power out on the downward or upward movement of the duck or anywhere in between.

(3) A 'Capsize Restoring Spring'. When a large negative displacement signal is being fed back to the duck, it can be pushed over backwards and being held by the torque will not return. This circuit inverts the displacement signal at a point one can vary, so that beyond it the signal is positive and acts to restore the duck's equilibrium. The rate of this 'spring' is also variable. D0018 does not require this because of its hunched back.

Circuit Description

Op amps 1 and 2 control the polarity sensitive gain change. A diode selects the resistance between the wiper and one end of the pot for positive signals - negative signals reverse bias this diode but negative feedback comes through the other diode and the other half of the pot.

Op amps 5 and 6 set the voltage limits to which the non-inverting input of 3 can be driven by the output of 2. The output of op amp 4 is a reference feeding the top of a pot to ground - the wiper is buffered by op amp 5 and sets the positive limit. No. 6 inverts the output of 5 with a variable amount of gain to set the negative limit. The output of 3 is thus the torque signal with limits and gain balance.

The duck displacement signal is fed to op amp 7, and from 8 we get our new signal with the capsize restoring spring added. At this point in the circuit clockwise displacements are positive therefore the point at which the spring has to operate is a negative voltage. This is set by op amp 10. Nos. 7 and 8 have a positive gain of 1 at voltages more positive than this point, but when the input goes more negative, dVout/dVin becomes negative. The gain is set by the 10K variable resistor to between 0 and -5. Use of this circuitry plays merry hell with the torque-displacement diagrams.
SWITCHABLE CHANGES TO DYNAPUY CHARACTERISTICS

COMPRISING:
- VARIABLE RATIO OF +/- TO - TORQUE SIGNAL
- VARIABLE TORQUE LIMIT, WITH VARIABLE +/- RATIO
- VARIABLE DUCK CAPSIZING RESTORE SPRING

* = SELECTED TO -1%

POWER SUPPLY 115V, OV
BACKBONE PITCH SIMULATION

Preamble

The SHP rig has two mechanical degrees of freedom, surge and heave. Provided that there are no external appendages it is more convenient to model the pitch mode electronically.

The technique follows conventional analogue computing methods. The "backbone" is simulated by a circuit whose output is a function of a forcing input and variable amounts of feedback corresponding to inertia, damping and spring. The force applied is the torque reaction of the power take-off from the duck and the feedback is set to model a real backbone of some sort. The computed angular velocity of the backbone (P) is subtracted from the duck's angular velocity (θ), and new duck displacements and accelerations are computed from (θ - P). In this way the duck's dynamic behaviour is referred to the "backbone" position rather than the horizon, as it would probably be in the full size machine, and we have signals telling us about the movement of the "backbone".

Circuit Description

Op amp 1 is where all the angular forces on the backbone are summed. Op amps 2 and 3 with S1 control the amplitude and polarity of the feedback round op amp 1 whose output corresponds with acceleration. Op amp 4 integrates this giving us velocity which can also be fed back in different amounts with different polarities. Finally, op amp 7 integrates velocity to compute displacement, and 8 and 9 control displacement feedback.

Using this circuit we can do the following things. By varying the amount of positive acceleration feedback we can alter inertia; velocity dependent feedback enables us to control damping; displacement dependent feedback controls spring rate. If we knew the torque reactions from phantom sibling ducks we could add them as extra forcing functions to the mixture.

The metering circuit reads either the mean or instantaneous value of any of the three backbone pitch parameters.
BACKBONE PITCH SIMULATION.

S1, S2 and S3 control polarity & gain (×10, ×100, ×1000) of P, P & P
feedback.

S4 selects meter input
S5 selects mean or inst. to meter.

* = selected to .12%
Power supplies ±15V, 0V

DE JEFFREY 4-8-70
MIXED SPECTRUM GENERATOR

Preamble

A real sea is composed of a mixture of waves at different frequencies and coming from different directions. To add realism in modelling duck environments we have constructed a generator which enables us to put in many different frequencies at once; unfortunately, the width of our present tank precludes more than one direction.

Pierson and Moskowitz and others have produced sets of equations which predict the frequency spectrum of seas for any particular wind speed. We can model these spectra using twenty closely spaced oscillators whose amplitudes can be individually varied to drive the wave-maker. What we produce is a comb spectrum, whose teeth are separated by a frequency difference of 5 to the power of one nineteenth—about 8%.

The component cost of this unit is about £100. The oscillator frequencies are not exact multiples of some low frequency and so the sequences do not repeat. Digital techniques using switch-tailed shift registers can be used to make pseudo-random seas of any chosen repeat time and are probably more versatile.

Circuit Description

The 8038 waveform generator is the heart of the mixed spectrum generator. There are twenty of these, each tuned to different frequencies in the range .5 to 2.5 Hz. An overall frequency shift is made possible by a ten turn pot (top left of dia.) which sets the voltage being fed to the frequency inputs of the oscillators. In addition, opening switch S1 open-circuits the .068 microfarad capacitor in the tuning circuit leaving only a 690 picofarad in place. This multiplies all the frequencies by 100 for use in fast analogue computer models.

All of the odd number oscillators are fed to the summing junction of op amp 3 via resistors selected by S2. This switch allows eleven stepped gain settings for each oscillator. The even numbers go to op amp 4 in an identical fashion. Op amp 5 sums all of the oscillators together, while S3 selects odd numbers, even numbers, or all together, before feeding to the main attenuator and output stage.
PIERSON-MOSCOWITZ MIXED SPECTRUM GENERATOR

S1 - DIVIDES FREQ BY 100
S2 - SETS LEVEL OF ANY 1 SPECTRAL COMPONENT.

11 RS ARE: 3K3, 3K9, 4K7, 5K6, 6K8, 8K2, 10K, 12K, 15K, 18K & 22K

S3 - SELECTS
10 ODD NO. OSCS
ALL 20 OSCS
10 EVEN NO. OSCS

POWER SUPPLIES: ±15V, ±7.5V, 0V  ALL LOGIC CHOS  DC: JEFFREY 17-8-76
WAVE POWER MEASUREMENT IN A NARROW TANK

Preamble

The direct measurement of incident power on a device in a wave tank is very useful in wave power work.

The power in a travelling wave is

\[ P = \frac{2}{3} \frac{\rho g T^2 (H_{rms})^2}{W} \]

where \( W \) = width, \( \rho \) = density of water, \( g \) = gravity, \( T \) = period and \( H_{rms} \) = wave height.

Removing constants, \( P \propto (H_{rms})^2 T = (H_{rms})^2 \omega / \omega_rms \)

This is easily computed if we have a wave height gauge and are dealing with single frequency waves. In a mixed sea where several frequencies are present at once the problem becomes more difficult. The \( H^2T \) box is our solution.

\( H_{rms} \) does not distinguish between incident and reflected waves.

Circuit Description

Assuming that water height varies sinusoidally in the presence of a single spectral component, a wave gauge will give us an output voltage

\[ V = \sqrt{2} H_{rms} \sin(\omega t) \]

Integrating (see op amp 3) gives

\[ V_1 = \sqrt{2} H_{rms} \cos(\omega t / \omega) \]

Integrating has put \( \omega \) into the denominator, which we want, but has shifted \( \sin(\omega t) \) through 90° into \( \cos(\omega t) \).

Pairs of op amps 1, 2 and 4, 5 both form all-pass phase shifting networks. Their inputs are respectively \( V \) and \( V_1 \) which they transform to remove the 90° difference between the sin and cos parts. By their nature these networks are only accurate over a limited frequency range. We were able to achieve a maximum error of 1° between .8 Hz and 2.5 Hz.

The two in phase signals can now be multiplied together. This gives us:

\[ 2(H_{rms})^2 \sin^2(\omega t / \omega) \text{ whose mean value is } (H_{rms})^2 / \omega \]

Op amp 14 filters out the periodic component to leave us the mean. This is scaled up to our calibration of 100 milliwatts per Volt.

The only frequency restriction we have imposed is the range of the phase shifters. Within this limit the circuit is correct for any spectral component and therefore for a mixed spectrum sea.

Switches 1 and 2 control the pre-multiply gain and post-multiply attenuation stages (op amps 6, 9, 12 and 13). Op amps 7, 8, 10, and 11 measure the absolute values of the two multiplier inputs, and the CMOS flip-flips latch an LED indicator on if they are too high. (For a more detailed discussion on multiplier conditioning, see page 24.30.)

Switch 3 controls four extra gain steps to bring the output voltage up in level should it be very low.
The integration of analogue signals over a long period presents problems. Op amp integrators work well only for short periods, measured in minutes, and for best performance they need to be designed for a particular period.

It is now possible to buy very linear voltage controlled oscillators. An accurate integrator can be made by modulating one of these with the signal of interest, and accumulating the number of pulses in a counter. If an eight digit counter such as our Bradley type 234 is used, one per cent resolution is possible over periods varying in a ratio of $10^5$:1 without having to touch any knobs. It is most convenient to work in periods of $10^8$ seconds (which can often be had very accurately in the counter) but with some prescaling or post calculation this is unnecessary.

The offset drift of an integrator is equivalent to the zero voltage count ratio of the oscillator, but by using digital counting there is no limit to the time of integration.

The ratio of two integrations can be had directly if the counter has an external clock input. We use this technique to calculate the long term efficiency in a mixed sea - the power in the sea is computed and presented as a varying voltage, as is the power from the duck. Both have the same scale. Sea power modulates the oscillator feeding the external clock input, while the duck power oscillator goes in through the front. Duck power is counted until the sea power reaches a count of $10^8$ (preset by the timebase switch), when the number displayed is a direct measure of efficiency.

The Bradley counters are no longer available but there are many equivalents costing about £1.50.
**LONG TERM AVERAGE EFFICIENCY METER (FOR MIXED S#S)**

**USING VOLTAGE TO FREQUENCY CONVERTERS AND FREQUENCY COUNTER FOR LONG TERM INTEGRATION.**

**POWER: +15V,0V**

OC JEFFREY 8-270
PEAK AND AVERAGE READING METER

This is usually used with the force signals from the duck mounting.

Circuit Description

Op amps 6 and 7 are low pass filters which remove the alternating component of the wave forces - this is used to reveal any longterm heave or surge effects which might, for instance, affect mooring considerations. Results, using this circuit, are seen in Section 17.

Op amps 2 and 3 are used to detect the lowest voltage excursion (peak V-). The output of the integrator is compared, in op amp 2, with the incoming signal and if higher is driven more negative. A pot is provided to reduce the integrator drift or cause it to drift at a fixed rate. This is useful when checking for peak force repeatability. S1 resets the integrator to the value of V1N and is usually pressed in quiet water.

The highest voltage excursion, peak V+, is dealt with in the same way by op amps 4 and 5.

The entire circuit is duplicated to allow one to be dedicated to heave forces and another to surge.
PEAK AND AVERAGE READING METER. (USED FOR FORCE MEASUREMENT)

MEASURES V AVERAGE (VAV), PEAK POSITIVE EXCURSION AND PEAK NEGATIVE EXCURSION TO EITHER SIDE OF VAV.

S1-S2 - RESET PEAK READING VOLTAGES.

POTS - ZERO INTEGRATOR DRIFTS TO ALLOW LONG PEAK HOLD.

POWER SUPPLIES 215V, 0V

D.E. JEFFREY 23.5.76
VARIABLE PHASE LOW FREQUENCY OSCILLATOR WITH SYNCHRONISATION

Preamble

At the heart of our narrow tank testing set-up is a Transfer Function Analyser. This gives a sinewave output and measures input signals in terms of sinewave amplitude, and phase relative to its output. Unfortunately, it only has one output. To drive a model backbone with signals of the same frequency but different phase we have had to construct an oscillator which is synchronised to the TFA but whose output can be varied in phase. It can also be operated without a synchronisation input, and as a versatile low frequency oscillator has much to commend it. It operates between .5 and 5 Hz.

Circuit Description

Op amps 2, 3 and 4 form a simple two integrator and inverter loop. Its frequency is varied by varying the time each integrator is operating - the CMOS 4016 circuit switches the inputs to the two integrators on for 640 fixed lengths of time per complete cycle. The length of time is set by CMOS 4047 monostable no. 1 or 2. The pulse width of 1 is twice that of 2 and consequently the frequency of the oscillator is double when 1 is used.

Initially, positive feedback was used to start and maintain oscillation; however, it proved impossible to reconcile the two requirements of low distortion and fast turn on time with this technique.

What we did instead was the following. Once every cycle CMOS monostable no. 3 sets integrator 1 to zero and the output of integrator 2 to a voltage set by the master gain. This is done again using the CMOS analogue gate 4016. If the pulse length of the frequency monostables is adjusted correctly, and their number of pulses per cycle is 640, these switches are making at the instant the voltage across them is zero. Consequently, there should be no more than a very small glitch visible on the output waveform of the oscillator, due to the .5 millisecond that the switches are on.

There is a square wave output from the TFA which can be used to set the integrators, and at the same time a frequency at 640 times that of the Transfer Function Analyser is available in the oscilloscope control box. This is used to trigger the frequency monostables. When operation without sync. is required, Switch 1 selects CMOS 4047 no. 4, used as an astable multivibrator and feeds it to the frequency monostables. Its output is divided by 640 using CMOS counter 4040 and two gates to detect the count and reset it - this reset pulse is fed to the integrator-setting monostable no. 3. The period of the oscillator is set by varying the resistor controlling the frequency of the astable no. 4.

The outputs of both integrators are taken through invertors, polarity switches and attenuators to a summing junction on op amp 11. In this way, any phase and amplitude can be selected by switching polarities into the appropriate quadrant and setting the real and imaginary amplitudes. This is done twice to give two independent variable phase and amplitude outputs.

The unit can be used to correct for wave-form distortion discussed on page 18.2.
GENERAL PURPOSE MULTIPLIER

Preamble

In our model instrumentation we often find that we have two voltages whose produce is important - i.e. power out of duck = angular velocity x torque. Occasionally, these voltages are static, in which case slow but accurate mark-space multipliers, such as the CIL Model 100, can be used. More usually, the voltages are time varying, requiring more bandwidth. Here we use multipliers which make use of the logarithmic characteristic of the current - voltage transform of a transistor.

These multipliers are very fast but are limited in accuracy. For instance, the Burr Brown 4203 K that we use has a maximum error of .6% of full scale. This represents 60 millivolts which would not be acceptable if the signal level was low. (The output is XY/10 volts so that 1 volt multiplied by 1 volt = 100 millivolts.) To avoid this problem we preamplify the signals before the multiplier and post-attenuate them. In this way, the multiplier always sees near to full scale signals although the output from the attenuators may be only a few millivolts.

Circuit Description

The feedback resistors for op amps 1 and 5 are selected by switches 1a and 2a. There are 12 varying from 10K giving a gain of 1, to 680K giving a gain of 68. Op amps 2, 3 and 4 take the peak absolute value of the X input to the multiplier and display it on a meter. It is calibrated to go off scale at 10V. The Y input gets the same treatment from op amps 6, 7 and 8.

In operation, switches 1 and 2 are treated as gain controls and turned up until the meters are nearly off scale. The output from the multiplier is fed to op amps 9 and 10, whose input resistors are selected by switches 1f and 2f. These resistors are matched in value to the feedback resistors in op amps 1 and 5 to better than .1%. This attenuates the signal, but not necessarily down to the level it should be at - factors of 10 of gain are introduced along with shifts in the position of the decimal point on the digital meter.

There are two stages of smoothing giving 24 dB/octave roll off. The DC is fed to a digital meter and a 270 scale meter, which has its own additional calibrated gain to give near to full scale readings.

In normal use the multiplier is set to read power out of duck calibrated in milliwatts.
12 RS 10k, 16k, 22k, 33k, 47k, 68k, 100k, 150k, 220k, 330k, 470k, 680k.
6 RS * * * * * * *= selected to ~1%

S1a and S2 preamplify & post attenuate signals to multiplier.

Power Supplies
+15V, 0V
DUCK EFFICIENCY METER

Preamble

This is the meter used in optimisation of a duck's performance. Given the same input data (wave period, wave height and power out of duck) one can get an accurate efficiency figure by calculation. The system described here uses analogue computation techniques and has the virtue of giving an immediate answer. It can only be used for single frequency waves.

If we remove all the constants and replace them with $K$, the efficiency formula becomes:

$$\text{efficiency} = \frac{P_{\text{duck}}}{H^2 T - (\text{atten. factor} \times H^2 T)}$$

where

$P_{\text{duck}}$ = power out of duck. This is available at the multiplier output.

$H$ = wave height. The averages of gauges A and B gives us this and ignores reflected waves.

$T$ = period.

Atten. Factor = the amount a wave is attenuated as it travels between wave gauges and duck. It is typically less than 5% and known for each frequency.

Circuit Description

Op amp 1 buffers the wave height input. (Wave height used is averaged and calibrated to read sine wave amplitude.) It goes into the first multiplier where it is squared and divided by 10. This is normal analogue multiplier convention which means that 4x0 full-scale inputs give a full scale output.

Op amp 3 buffers the duck power input. It is amplified by op amp 4 before being led to 2 which, with the second multiplier, forms a dividing circuit. The output of 2 is $P_{\text{duck}}/H^2$.

The switches, 1, 2 and 3, are there to correct for scaling switching on wave gauges and $P_{\text{duck}}$. This also accounts for the presence of op amps 4, 6 and 7.

Multiplying by frequency has the same effect as dividing by period and is more convenient here since the Transfer Function Analyser is calibrated in Hertz not seconds. The switch and pot marked "set to freq. of waves" vary the gain of op amp 9 and need to be correctly set for each frequency. This gives us $P_{\text{duck}}/H^2 T$.

The 5 K pot on 9's output compensates for tank attenuation, by increasing the gain in 10. It also needs to be set for each new frequency. A look-up table tells us what value it should have.

Op amp 10 is used to calibrate the signal before it is sent to the meter. Checks with electronic input signals show that the computation is reliable to 1%. We believe that the entire efficiency calculations are within 4%.
Duck Efficiency Meter

SI - Pre-Amplifies & Post Attenuates Pdyn.

S2 and S3 - Coupled to Wave Gauge Scaling Switches. Compensates for Gain Used To Bring Meters On Scale

5k Pot - Used to Compensate For Tank Attenuation.

Multipliers - C.I.L Model 100

* = Selected To .1%

Power Supplies ±15V, 0V

D.C. Jeffrey 5/8/76
THE SYNCHRONISED OSCILLOSCOPE SYSTEM

Preamble

Most of the families of curves used in this report were produced using our synchronised oscilloscope system. (See page 2.6.) It comprises two oscilloscopes, the Tektronix 604 and 603 monitors. The first has a long persistence P7 tube and the second a bi-stable storage tube. They usually run, in parallel as far as the X and Y axes are concerned, to show a complete single wave cycle per sweep. (They can also be run at 10 or 100 times slower.) In normal use the P7 'scope acts as a monitor and when the display has settled it is written onto the storage screen. It is possible to apply different mark-space patterns to the write command input, (the Z axis), and in this way we can distinguish between six different traces.

In random sea conditions, however, we cannot set up the stable conditions necessary to use the 'scopes in this way. To enable us to write simultaneously a number of traces a multiplexer is needed. Rather than having a small number of channels and complicated switching, we decided to multiplex all 60 possible input channels and control which ones are written on to the screen.

We use an Oxley pin programmeable matrix board as the central "telephone exchange" in our instrumentation system. It has 60 columns, which we use as inputs, and 28 rows usable as outputs. The bottom row (no. 30) has 60 individual pin contacts (they are not continuations of the columns) and these are what we use to control the channel selection for the multiplexer. Inserting a pin in this row not only brights up the required channel, but by having a particular resistor in the pin we can specify which Z pattern we want to identify it. Columns with no pin in them are not brighted up.
Circuit Description - The Ramp Generator

We decided to produce our ramp using a digital to analogue converter because it is very flexible. The simplest way to drive it would have been by using a phase lock loop to multiply the wave frequency up to some convenient figure, count this and feed the outputs of the counter to the digital to the analogue converter. We tried this, but found the time required for the phase lock loop to settle was longer than we cared to wait; we therefore adopted the following technique.

Op amp no. 1 converts the output from the signal generator driving the wave-maker into a CMOS compatible square wave. This drives monostable (4047) no. 1, which triggers monostable no. 2 after a delay variable from zero to one half of the longest wave period. This delay, coupled with the trigger polarity switch on the input, permits us to start the display at any wave phase angle. Monostable no. 2 stays true for about half a millisecond, driving one of the 4016 bilateral switches on to sample and hold the output of op amp no. 3 on the capacitor buffered by op amp no. 4. At the end of this period monostable no. 3 is triggered. It too stays true for half a millisecond and drives a switch which resets the integrator around op amp no. 3 to zero - it had been integrating a constant current for one whole wave period before being sampled; the voltage held on op amp 3 is thus proportional to the wave period. Op amp no. 5 calibrates it to 5 volts per second.

The reciprocal of this period voltage is taken by the multiplier - it gives a voltage proportional to frequency, which is scaled to 3 volts per Hz. It drives the VCO section of the phase lock loop IC, 4046, whose output is 640 cycles per wave. This frequency is divided by 10 two times and switch S3 selects whether f/1, f/10 or f/100 is fed to the binary counter 4040, whose ten most significant bits are fed to the digital to analogue converter. The output of this converter is the X ramp.

When the S3 has selected 1 wave per sweep, resetting the counter is done by the output of monostable no. 3. This cannot be done for either a 10 or 100 wave sweep, so here we detect the count of 640 and use it as a reset signal. The flip-flop 4013 ensures that the sweep always starts with the correct phase by holding the counter at zero until the next synchronised pulse from monostable no. 3.

A fourth position of S3 permits a high speed unsynchronised sweep which will ultimately be used with histogram and spectrum displays.
**Sync'd Scope Ramp Generator**

*For use with A.F. Sig. Gen.*

- **S1 ON**: Input TTL Compatible
- **S2**: 180° Phase Shift of Sync
- **S3**: Selects 1 Wave & Per Sweep
  - 100 Waves
  - 1000 Waves
  - Unsync'd, for Histogram Display
- **PB. 4**: Resets Ramp to Zero

**All Logic CMOS.**

- Multiplier: C. L. Model 100
- D.A.: Non-Mod DAC 02

**Power Supplies**: ±15V, 0V
The multiplexer is based on the Siliconix DG 508. This integrated circuit has 8 inputs which can swing between + and - 15 volts, going to one output. Channel selection is via a 3 bit address, CMOS compatible, and an enable line which permits several devices to have a common output bus. We use eight of them to give a maximum capacity of 64 channels.

Channel selection is done by a 4520 counter. The three least significant bits are bussed out as the address lines to all eight ICs, while the next three bits are decoded into eight individual enable lines by binary to octal decoder 4028. In parallel with the multiplexer ICs, eight 4028s are addressed and enabled. Thus every analogue channel has a corresponding digital output which is true only when that channel is selected.

The first 60 of these digital lines are fed to the 60 individual contacts on the bottom row of the Oxley matrix board. The common line is connected to the non-inverting input of the Z level op amp. When the operator inserts a resistor pin between a contact and the common line, and its digital output goes true, current will flow and the Z level voltage will change. We can use 6 different resistor values to give different Z levels. CMOS is convenient in that its unloaded logic states are 0 V and +15 V.

S1 to 6 select the binary number which will reset the 4520 counter to zero. It is normally set to 61. The reset pulse is phase locked with the 640 pulses per wave signal from the ramp generator, and the phase lock oscillator clocks the counter. In this way all channels are selected 640 times per sweep.

The two monostables respectively allow 5 microseconds to elapse after a new channel is selected and provide an 8 microsecond write command for the Z modulation of the two 'scopes.
MULTIPLEXER

(ONLY 8 CHANNELS SHOWN)
PROGRAMMABLE FOR 1 → 64 CHANNELS IN BINARY ON S1 → S6.

ALL LOGIC CHIPS

ALL CHANNELS SAMPLED 640 TIMES PER WAVE.
PIN RESISTORS SET Z-LEVEL VOLTAGE. (SEE Z-MODULATION SHEET)
VALUES = 150K, 75K, 51K, 39K, 30K, 27K

POWER SUPPLIES ±15V, 0V

D.C. JEFFREY 12.8.76
Z MODULATION

On a storage 'scope, the screen is bistable and either writes or doesn't. Trace identification has to be done by mark-space variation. The 4040 counter is run in parallel with its mate in the X ramp generator, and the various gates coupled to its output lines give recognisably different patterns when used to Z modulate a line on the 'scope. The six 3130 op amps are all used as comparators, comparing the Z level from the multiplexer with six different references. All the comparators whose references are below the Z level will be true and all those whose references are above will be false - the only exclusive OR gate to go true will be the one which straddles the Z level. Thus a particular resistor in the Oxley pin will select one of six different patterns.

The push button is pressed to write a signal on the storage 'scope during the next sweep. It sets the first flip-flop in 4013 true, and the next \( \overline{X} \) return pulse clocks the second true and gates the write signal to the storage scope. It also resets the first flip-flop so as to inhibit writing after the following \( \overline{X} \) return pulse.

Thus a point is written on the 'scopes if:

(a) that channel is selected by the multiplexer
(b) it has a resistor pin
(c) the selected pattern is true at that point
(d) if \( \overline{X} \) return is true
(e) if the multiplexer write is true

and in the case of the storage 'scope

(f) if the push button was pressed during the last sweep.
P.B. - WRITE NEXT SWEEP ON STORAGE SCOPE
640 HZS/WAVE & RETURN FROM 'RAMP GENERATOR'

ALL LOGIC CHIPS

POWER SUPPLIES +15V, 0V
OBJECTIVES FOR 1976/1977

Increased Torque

From our preliminary work with mixed spectra it looks as though we need more torque than is available from the Aeroflex V25Y6 torque motor. D0019 will use the VBT 34M from Vernitron, an increase by a factor of five.

Power Take-Off

There is a shortage of variable displacement hydraulic pumps with power levels suitable for tenth scale work. It ought to be possible to get energy in pulses from a fixed displacement pump in a way which confers the benefits of smart power take-off and produces the right sort of forces on the backbone. We shall try to develop the control unit using electronic techniques at one hundredth scale. It is important to solve the problem before we finalise the tenth-scale string design. The ideal dynamometer would allow us to change damping and spring rate settings from the beach. But if we cannot have that then we must at least have a good approximation to the best fixed settings available.

Efficiency Measurement in Realistic Spectra

With the new computer equipment we will be able to measure spectra as well as sine waves. We may find that mixed seas raise some new aspects of duck design. We must produce results for various sea states in terms of power and force histograms.

Extreme Wave Tests

The 24 inch wave-maker will allow tests in waves with heights greater than a duck diameter. We will be interested in backbone forces, recovery from capsize and the onset of drag force take-over from inertia force.

Hydrodynamic Coefficients

Some of our best friends are mathematicians. With the right inducements and coefficients we might be able to persuade them to analyze ducks using the technique described by Bishop and Price (9). What we have to do is excite the ducks in heave, surge and nod while noting the velocities and forces induced. We already have the results for nod force to nod velocity which show an extraordinary and desirable increase in nod inertia at low frequencies (see page 21.3). Measurements are bedevilled by tank reflections and we need to do further work on beach design or else work between side cheeks in a wide tank.

Dummy Ducks

Experiments in short-crested seas at both tenth and hundredth scale would be very much cheaper if it were possible to make a passive appendage which induced in the backbone the same sort of forces as do our favourite ducks. The ideal would be a shape which could clip on to a cylinder.
Wriggling the Stern

Ogilvie (10) has shown that a submerged cylinder rotating about an eccentric axis makes waves on one side only. Evans suggests that in reverse this would make an excellent wave absorber and he has demonstrated it with the surging-heaving rig. They explain how the phenomenon arises by arguing as follows. The circular motion of the cylinder could be produced by giving it simple harmonic motions in the heave and surge directions which are 90° out of phase with each other. The waves produced by the heave motion alone would be in phase fore and aft of the cylinder while the waves produced by the surge motion alone would be in antiphase. When both motions combine the waves on one side are additive while those on the other cancel.

Now the motions of the backbone of a non-rigid duck string might also be considered as separate simple harmonic motions. The phase of the movements which we have measured so far on the surging-heaving rig are such as to produce an Ogilvie wave astern and so lose power. But if we were able to reverse the phase of the response in either axis then the opposite would be that the stern of the duck could behave like the passive side of Ogilvie's cylinder. We have shown that surge forces are resistant to phase manipulation. The only approach would be to fiddle with surge movements via stiffness and inertia. But we have also shown that heave forces can be reversed (see page 8.5) by playing off buoyancy against inertia. At present buoyancy dominates the behaviour of ducks but an increase of added inertia in heave would reduce this. It could be achieved by some suitably designed appendages rather like those in Nature, June 21, 1974. It will be extremely interesting to try a combined attack using natural frequency and appendages to produce a non-radiating stern. One of the difficulties of implementing Evans' suggestions is the requirement for a power take-off mechanism with two degrees of freedom. This can be implemented rather crudely by nodding ducks on a flexing backbone. The transfer of work from heave to nod is quite good at low frequencies. We get efficiencies of about 75%. In surge the transfer is only about 25%. Power which goes into bending a backbone is by no means lost.

Wave-maker Orchestration

A few more months with the surge-heave-pitch rig should finish, for the time being, our work with single ducks. The next stage will be the orchestration of a wide tank. We have to show that Huygen's principle applies and that phase increments to the drive signals of a bank of wave-makers can produce oblique wave fronts. We have to make a control unit which will allow straight-forward settings for directional characteristics of a sea. The delivery of the first batch of ICE wave-makers to Riccarton is imminent.
Backbone Tests

Even without dummy ducks the behaviour of a plain cylindrical backbone in mixed seas will be extremely interesting and is the first item on the list for tests in a wide tank. We plan to use sixteen 10 cm diameter sections 0.5 metre long with the three-ball version of the Wood joint between each section. The pre-tensioning load will be adjustable. Each joint will contain piezo-electric bending moment sensors and the velocities of backbone movement in heave and surge will be recorded at intervals along the length. Our first tests will be in the simplest of short-crested seas which will consist of just two converging wave fronts. The results will go towards improvements in the theoretical analysis and the settings for more surge-heave-pitch rig tests.

Tank Building

After our two months with the backbone experiment at Riccarton we will have to make the final decision about whether or not to build a wide tank at Edinburgh. It is always a problem to decide how much time to spend building instruments now in order to save time during testing. There can be no doubt that building a wide tank with proper control of directional spectra is a major piece of work. If we go ahead it will be our main area of activity in 1977.
The object on the left of the photograph is a torque motor. We use two of them for power take-off. They consist of a toroidal coil and a bar magnet. They generate a voltage proportional to the angular velocity at which they rotate and they give a torque proportional to the current with which they are driven. They can work through an angle of 120°. Careful tests show some small hysteresis effects not mentioned by the manufacturers but they are extremely useful for wave power work.

The torque motors are mounted inside the two housings shown to the right of the duck. We can get away with ball-races for the magnet spindle thanks to the 'Cimplus' in the tank water. The motor housings are allowed to flood.

Some slits are cut in the outer shell of the housings and the metal between the slits is pulled outwards. This makes them a comfortable fit in the recesses in the end of the duck.

We calibrate the voltage generators by clamping the housings in the centre of a graduated plate. A radial arm is screwed to the rotating part and moved through precise angles. The velocity signals are taken to an operational amplifier integrator. Provided that the usual precautions are taken to prevent drift this gives excellent static calibration.

The torque half of the dynamometer is calibrated with a radius arm driving the pan of an accurate weighing machine. It is necessary to know the value of g to get from kilograms to Newtons. In Edinburgh it has the value 9.8158.

The brass rods to the right of the picture are ballast weights which fit inside the tubes which run through the duck. The centre of gravity is adjusted by trial, error and intuition for best results. Outline drawings are on page 19.2.
Ducks are made by enclosing a loop of stainless steel shim inside a stockade, and inserting tubes for weights and dynamometers. All the interstices are then filled with an expanding polyurethane foam.

The dynamometer consists of a pair of brushless torque motors which plug into the ends of the model to be tested. One is used to generate a velocity signal and the other is driven with a current to supply an opposing torque. Power is the product of torque and velocity. Characteristics can be modified by controlling the transfer function between velocity and torque. The simple condition is with torque proportional to velocity but interesting changes occur with frequency dependent amplitude and phase changing networks. Such ducks are called 'smart'. The imperfections of practical hydraulic systems may also be modelled. Electronics are discussed on page 24.14.

On each side of the mounting, vertically above the axis of the duck, are transducers consisting of strain gauges on a thin-walled phosphor bronze torque tube. They respond to surge forces. Another pair to the left of the photograph respond to both heave and surge. With a little analogue computing one can separate them. There is a reaction on the strain gauges from torque in the dynamometer. As the distance to the axis is known it can be corrected by a signal proportional to the current output of the torque drive amplifier.

The mounting can be adjusted vertically to change the axis depth of the models. This is one of the adjustments used in tuning a duck. It can also be used for measuring heave spring rate. Some experiments are mentioned on page 17.6.
OPERATOR'S TEST BENCH

We make extensive use of electronic instrumentation. Details of the circuitry are given on page 24.1 onwards.
A PAIR OF HEAVING FLOAT GAUGES

A straight-line linkage constrains a light rolled paper float to move vertically. The float velocity is sensed by a pair of microammeter movements. Electronic circuitry is discussed on page 24.4. These wave gauges can resolve waves down to .02 mm which are hardly detectable to the eye. They are unaffected by meniscus problems and have proved extremely stable. They take an average of waves right across the tank which avoids the problems of the diamond wave pattern which seems to be caused by the meniscus where the wave crest meets the glass side of the tank. An example can be seen in the photograph. The diamond pattern is an example of cross waves which make single point wave gauges tedious for wave power work.

The gauges are always used as a pair and are set at one quarter or three-quarters of a wavelength apart with the aid of the scale stuck to the side of the tank. They can be locked together and moved along the tank so as to maximise the difference between the magnitude of their outputs. At this point the mean of the outputs is the incident wave and half the difference between them is the reflected wave.

They show a resonance at about 5 Hz and so would be over-reading by several per cent at the test frequencies giving pessimistic efficiency figures.
HEAVING FLOAT WAVE-GAUGES MEASURING A STANDING WAVE

This is a time exposure with tracer particles injected into the water. The gauge on the left is on a node and the water movement below it is horizontal. The water is lit by strip lights from below. Lines caused by 100 Hz ripple from the lights can be seen within the envelope of the standing wave.

Absorbing wave-makers can produce standing waves which are stable to better than 1%.
A QUADRILATERAL LINKAGE WAVE-GAUGE

This is a time exposure. The reader may find it difficult to interpret but it is worth the effort. The circles are made by a tracing fluid which is a mixture of Carbon tetrachloride and Xylene of the same density as water. They show a wave travelling from right to left in deep water. Notice the change of orientation of the gap in the circles across the picture showing the spatial phase differences.

The broad band of light across the middle of the picture is the envelope of the meniscus. It is lit by the strip-lights below the tank and 100 Hz stroboscopic effects are evident.

Contact with the water is made by a T-shaped balsa wood float which is constrained by a linkage of the same material. It can heave, surge, pitch and roll but yaw and drift down the tank are gently restrained. Its velocities in heave and surge may be resolved from the signals from the two microammeter movements. (See circuitry on page 24.18.)

This gauge is the most promising design for measurement of incident and reflected energy in mixed seas.
A SELECTION OF MODELS AND APPARATUS

Notice the awful fate of D0013.
For ducks whose backbones have no external appendages, pitch can be modelled electronically using conventional analogue computing techniques as discussed on page 24.18.

The heave and surge motions are transmitted to two horizontal spindles. Heave is constrained by a straight-line linkage but surge is a short arc of a circle which is straight enough for the centimetre or so of movement encountered so far. Friction is reduced to very low levels by the use of leaf springs, point joints and ball-races.

Each spindle can have its inertia increased by the addition of pairs of weights. Its stiffness can be controlled by the length and thickness of torsion springs which are contained in rotatable housings used for adjusting axis depth and surge position. We also provide torque motors which can modify stiffness, damping and inertia electronically as well as putting force command signals onto the duck's backbone. A set of strain gauge transducers measure heave and surge force close to the duck.

There are two channels for measuring backbone movement. Our usual microammeter transducers measure velocity, which can be integrated to give a short-term position signal but there are also zero frequency transducers made from strain gauges on the microammeter drive linkage. Electronic circuitry is discussed on page 24.14.

The rig is by no means a perfect simulation of a backbone and there is some question about the values of stiffness, inertia and damping used to restrain the spindles. But it does show that ducks can work on a moving axis and that Ogilvie's cylinder can absorb. It allows us to measure some useful coefficients for theoreticians and is probably the most realistic way of using a narrow tank. We could spend another happy year working with it and we expect to return to it after some tests in a wide tank.
REFERENCES


(7) Herbich, J.B. Experimental studies on wave filters and absorbers. Office of Naval Research Contract to The University of Minnesota Nonr-1710/05 January 1956.


Other papers of interest

Mei, Chiang C. Power extraction from water waves. J. of Ship Research, 2, pp 63-66, June 1976
