PRINCIPLES FOR CAPTURE OF ENERGY FROM OCEAN WAVES. PHASE CONTROL AND OPTIMUM OSCILLATION.

J. Falnes
Department of Physics, NTNU, N-7034 Trondheim, Norway

1. Absorption of waves means generation of waves.

A body oscillating in water will produce waves. A big body and a small body may produce equally large waves provided the smaller body oscillates with larger amplitude. This may be utilised for the purpose of wave energy conversion, for instance by a small floating body heaving in response to an incident wave, in particular so if it can be arranged that the body oscillates with a larger amplitude than the wave amplitude.

Generally it can be said that a good wave absorber must be a good wave-maker.[1] Hence, in order to absorb wave energy it is necessary to displace water in an oscillatory manner and with correct phase (timing). This can be obtained by an oscillating body as explained above. Alternatively, wave generation by oscillatory displacement of water can be obtained, for instance, by an oscillating water column (OWC) in a fixed chamber having an opening into the sea. It is also possible to enclose the water by blocking the chamber opening with an elastic or flexible bag, which can oscillate under wave action. In such a case sea water in the chamber is not necessary; it can simply be replaced by air in which the pressure oscillates in step with the motion of the flexible bag.

Absorbing wave energy for conversion means that energy has to be removed from the waves. Hence there must be a cancellation or reduction of waves which are passing the energy-converting device or are being reflected from it. Such a cancellation or reduction of waves can be realised by the oscillating device, provided it generates waves which oppose (are in counter-phase with) the passing and/or reflected waves. In other words, the generated wave has to interfere destructively with the other waves. This explains the paradoxical, but general statement that “to destroy a wave means to create a wave”. An illustrative example, where 100 % absorption of wave energy is possible, is shown in figure 1. This corresponds to an infinite line (perpendicular to the figure) of oscillating small floating bodies, evenly interspaced a short distance (shorter than one wavelength). Complete absorption of the incident wave energy is possible also with an elongated body, of cross section as shown in figure 1, and aligned perpendicular to the plane of the figure, provided the body oscillates vertically and horizontally in an optimum manner.

It can be shown theoretically[2,3,4] that only 50 % absorption is possible if there is only the symmetrical radiated wave, as shown by the curve b in figure 1, when the wave is generated by a symmetrical body oscillating in only one mode of motion, the vertical (heave) oscillation. Likewise, if there is only the antisymmetric radiated wave (curve c) from the symmetric body, more than 50 % absorption is theoretically impossible. However, if a sufficiently non-symmetric body is oscillating in only one mode of motion, it may have the ability to absorb almost all the incident wave energy. Salter had come rather close to this ideal condition with his experiments on the Duck.[5]

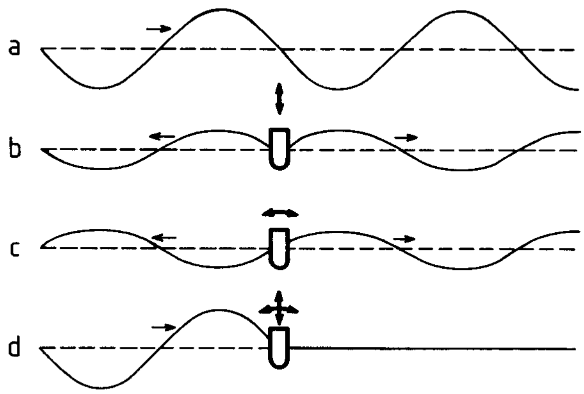

Figure 1. To absorb waves means to generate waves. Curve a *represents an undisturbed incident wave. Curve* b *illustrates symmetric wave generation (on otherwise calm water) by means of a straight array of, evenly spaced, small floating bodies oscillating in heave (up and down). Curve* c *illustrates antisymmetric wave generation. Curve* d*, which represents the superposition (sum) of the above three waves, illustrates complete absorption of the incident wave energy.*[1]

Another example is shown in figure 2. Here a heaving point absorber, absorbing wave energy, has to radiate circular waves which interfere destructively with the incident plane wave. A "point absorber", which may be a heaving body, is (by definition[6]) of very small extension compared to the wavelength. The maximum energy which may be absorbed by a heaving axi-symmetric body equals[2,3,6] the wave energy transported by the incident wave front of width equal to the wavelength divided by 2π. This width may be termed the "absorption width". Early experimenters, not being aware of this relationship, were surprised by measuring absorption widths larger than the physical width of a tested point-absorber model. An alternative term to absorption width is "capture width", which we shall use for the smaller width corresponding to the useful energy, which is the absorbed energy minus energy lost by friction and other dissipative effects.

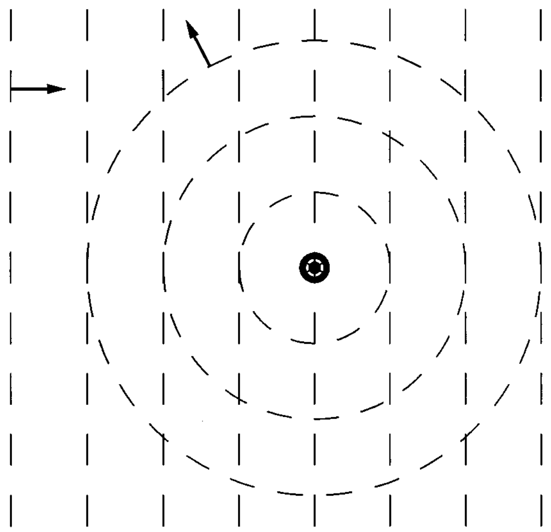

Figure 2. Wave pattern of two interfering waves seen from above. When a "point absorber" absorbs energy from an incident wave, it generates a circular wave radiating away from the absorber's immersed surface.

2. Optimum oscillation for maximum energy capture.

In order to obtain maximum energy from the waves it is necessary to have optimum oscillation of the wave-energy converter (WEC). For a sinusoidal incident wave there is an optimum phase and an optimum amplitude for the oscillation.[1]

To illustrate this, let us once more refer to figure 1. In this case the amplitudes of the radiated waves (curves b and c) have to be exactly half of the amplitude of the incident wave (curve a). Thus it is required that the amplitudes of the vertical and horizontal oscillations of the WEC have proper values. Note that these optimum amplitudes are proprtional to the amplitude of the incident wave.

Moreover, with optimum phase conditions for the two modes of oscillation, the two corresponding waves radiated towards right have to have the same phase (that is: coinciding wave crests and coinciding wave troughs). This also means that the symmetric and antisymmetic radiated waves cancel each other towards left. Furthermore, the phases of the two oscillations have to be correct with respect to the phase of the incident wave, since the crests of the waves radiated towards right (curves b and c) must coincide with the troughs of the incident wave (curve a).

For a case with only one mode of oscillation, such as heave, the resulting wave corresponds to the superposition (sum) of the waves a and b in figure 1. Then the optimum heave (vertical) amplitude and phase are the as above, in the case of two modes. The wave radiated towards left and the resulting wave transmitted towards right both have amplitude equal to half of the amplitude of the incident wave. Since wave energy is proportional to the square of the wave amplitude this means that 25 % of the incident wave energy is reflected towards left, and also 25% of it is transmitted towards right. The remaining 50 % is absorbed by the WEC, and this is the theoretical maximum, as mentioned previously.

A one-mode oscillating system happens to have the optimum phase condition if it is at resonance with the wave. That means that the wave frequency (reciprocal of the period) is the same as the natural frequency of the oscillating system. Then the oscillatory velocity of the system is in phase with the wave’s exciting force which acts on the system. This is illustrated by comparing the curves a and b in figure 3.

The optimum phase condition is approximately satisfied also for wave frequencies slightly off resonance, namely for frequencies within the so-called resonance bandwidth of the system. WECs of very large geometrical extension have broad bandwidths. In order to save materials (concrete, steel, etc.) it is desirable to utilise a WEC system of smaller physical size. A drawback with this is that the resonance bandwidth becomes rather narrow.

Thus for small-sized WECs it is very important to apply some form of phase control, in order to obtain the optimum phase condition, at least approximately. Phase control by latching is illustrated by curve c in figure 3. (It is assumed that the various floating bodies considered in figure 3 have equal water plane areas. But the heavier body has deeper draught.)

As mentioned and explained above, there is also an optimum oscillation amplitude in order for the WEC to absorb a maximum amount of energy. A somewhat smaller amplitude is required to maximise the converted useful energy, which is the absorbed energy minus some unavoidable lost energy (due to friction, viscosity, etc). Except for cases with small or rather moderate wave heights, this desirable amplitude may not be achievable due to the limited design amplitude of the WEC. In practice, the energy-handling capacity of the WEC’s machinery and other equipment is also limited. For economic reasons the WEC ought to be designed with specifications in such a way that it works close to its design limit a rather large fraction of its life time.[7,8] As a consequence much of the wave energy remains in the ocean, except during time spans of rather moderate wave activity.

Also for the case when the oscillation amplitude is limited by design specification, the absorbed energy, as well as the converted useful energy, is maximum when the oscillatory velocity is in phase with the exciting force due to the incident wave.

3. Phase control by latching.

In order to obtain the optimum oscillatory motion for maximising the absorbed energy or the converted useful energy it may be necessary to return some energy back into the sea during some small fractions of each oscillation cycle and profit from this during the remaining part of the cycle.[9] For this reason "optimum control" of WECs has also been termed "reactive control".[10] To achieve this in practice it is required to utilise a reversible energy-converting machinery with very low conversion losses. It could, for instance be a high-efficiency hydraulic machinery which can work either as a motor or as a pump.[11] To realise the optimum control in practice, a computer with appropriate programme software, and with input signals from sensors measuring the wave[1] and/or the WEC's oscillatory motion[10], is required. It is also necessary to predict the wave some seconds into the future.[12,13]

If the wave periods are longer than the WEC's natural period, optimum phase can, in a simpler way, but only approximately, be obtained by "latching phase control" which provides for a motion as indicated by curve c of figure 3. A clamping mechanism stops the motion at the instant of extreme excursion, that is at the instant when the velocity becomes zero. A release signal is applied to the mechanism a certain time (about one quarter of the natural period) before the next extremum of the wave exciting force. For a heaving buoy this force is approximately in phase with the wave elevation of the incident wave. Then the phase control should provide for the buoy moving upwards/downwards at the occurrence of a wave crest/trough.

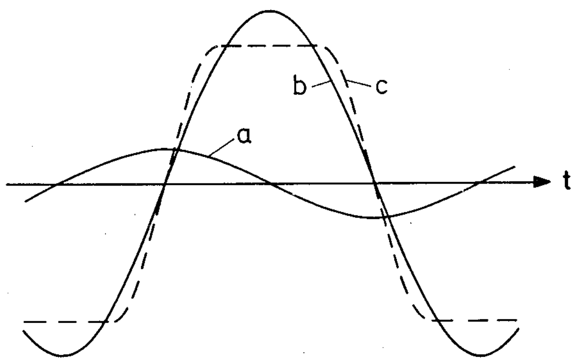

Figure 3. Resonance and phase control. The curves indicate incident wave elevation and vertical displacement of (different versions of) a heaving body as functions of time.

Curve a: *Elevation of the water surface due to the incident wave (at the position of the body). This would also represent the vertical position of a body with negligible mass. For a body of diameter very small compared to the wavelength, curve* a *also represents the wave's heave exciting force on the body.*

Curve b: *Vertical displacement of heaving body whose mass is so large that its natural period is equal to the wave period (resonance).*

Curve c: *Vertical displacement of body with smaller mass, and hence shorter natural period. Phase control is then obtained by keeping the body in a fixed vertical position during certain time intervals.*[1]

A mathematical simulation study[14] has been carried out on a scaled-down laboratory model of an OWC placed at the vertical end wall of a 0.4 m wide and 0.7 m deep wave channel. The width of the OWC is 0.18 m, and the rectangular area of the inner water plane and of the entrance mouth is 0.22 m^2. The upper edge of the mouth is at a depth 0.06 m. For a situation where the incident wave is sinusoidal with period 2 s, the oscillation of the OWC is as shown figure 4a without phase control and in figure 4b with latching phase control. It is seen that the excursion amplitude is significantly larger with control.

While a fairly close approach to the optimum phase is attained by the method of latching phase control, the amplitude may be less than optimum, because with this method there is no reversible energy-converting machinery to return desirable amounts of energy back to the sea during fractions of the oscillation cycle. This drawback is not, however, applicable with wave conditions where the WECs have to operate at its design amplitude, anyhow.

For the above-mentioned simulation study,[14] where amplitude limitation does not come into play, the energy absorbed is as shown by the curves in figure 5 for the three cases: no control, latching phase control, and full optimum control. For the latter case it is seen that relatively large amounts of energy have to be returned to the sea during two intervals of each oscillation cycle. The theoretical result is that, in the long run, the energy absorbed is about twice the absorbed energy with latching phase control. And this latter energy is about four times as much as without any control.

For real sea waves the time intervals between crests and troughs vary in a somewhat stochastic manner. With operation of a latching-controlled WEC in such irregular (non-sinusoidal) waves the release signal is determined by a computer with appropriate software. It is required to feed the computer by input signals from sensors measuring the wave or the wave exciting force. It is necessary that the computer is able to provide a reasonable prediction of the wave force a certain time into the future. Evidently, the decision to unlatch the WEC should be taken at least one quarter natural period before the next extremum of the wave force.

The principle of latching phase control of a heaving (vertically oscillating) body in irregular waves, is illustrated by the experimental results shown in figure 6. The experiment was run in a large laboratory wave channel, 10.5 m wide and 10 m deep. In this particular case the body was shaped as a cone pointing downwards. A piston pump inside the body was activated by the heave motion. Through a long rod the piston was connected to a universal joint on an anchor at the bottom of the wave channel. The cylinder of the pump was rigidly tied to the body and moved up and down together with it. Through the heave motion energy was directed through the pump and further through valves and a turbin to become useful mechanical energy on a rotating shaft. The hydraulically operated latching mechanism (functioning as a parking brake) could latch the body to the piston rod. Latching and unlatching signals were provided through a computer fed with signals from sensors measuring the body's heave motion and the wave beside the body. The height of the conical body was 2.3 m. With the body in its equilibrium position, the uppermost end of the body, where the diameter was 0.9 m, was 0.62 m above still water level. The rod diameter was 75 mm. The body had a mass 120 kg and a volume 0.5 m^3. The natural period of the body was about 1.0 s.

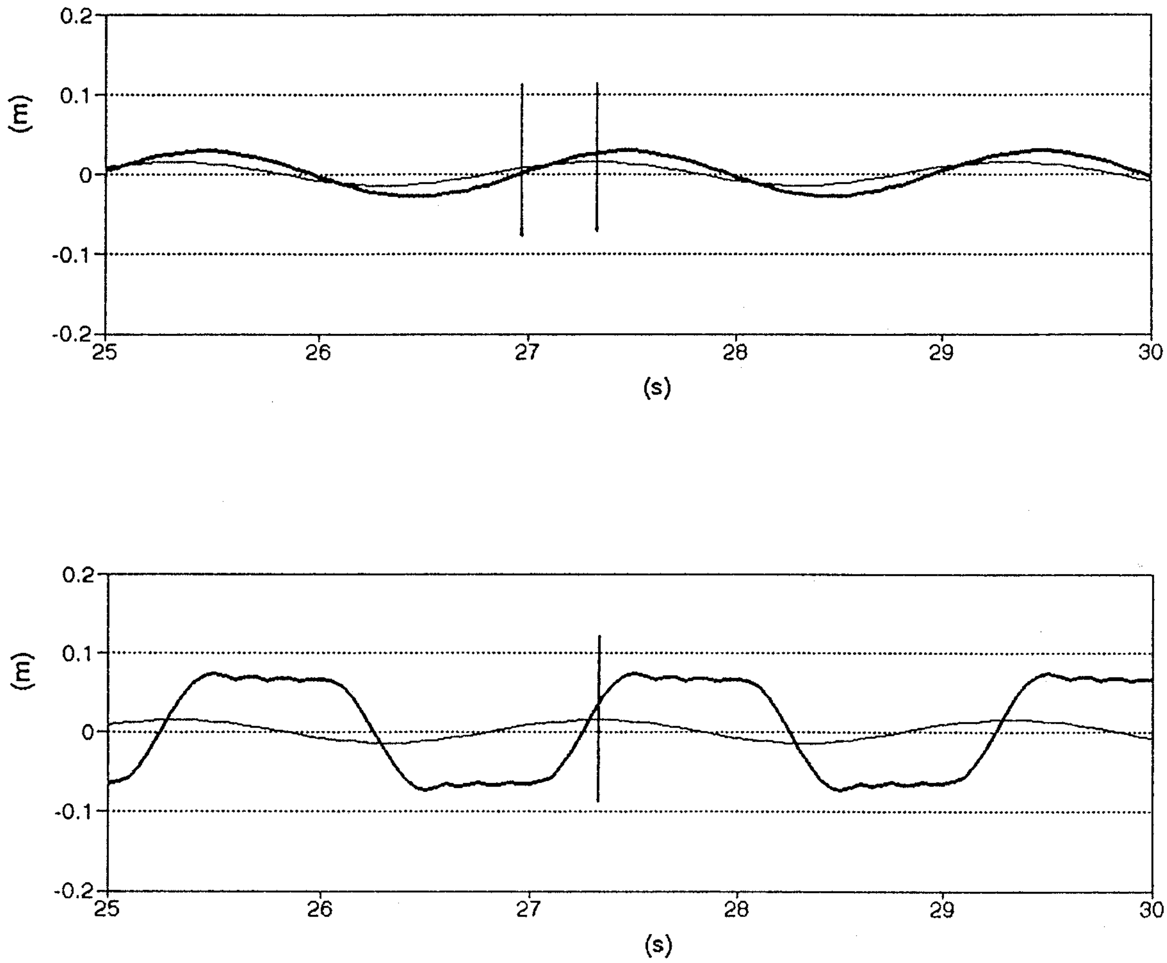

Figure 4. Vertical oscillation of OWC without (upper diagram) and with latching phase control (lower diagram). The thinner curve represents the incident wave (approximately in phase with the exciting force) and the thicker curve the ocillating position. Units are metres on the vertical scale and seconds on the horizontal. The right-hand vertical bar indicates the occurrence of a force maximum, and the left-hand bar the occurrence of a maximum in oscillation velocity. In the case of phase control these occurrences coincide. Then the velocity is in phase with the force, and consequently the overall oscillation excursion becomes larger.

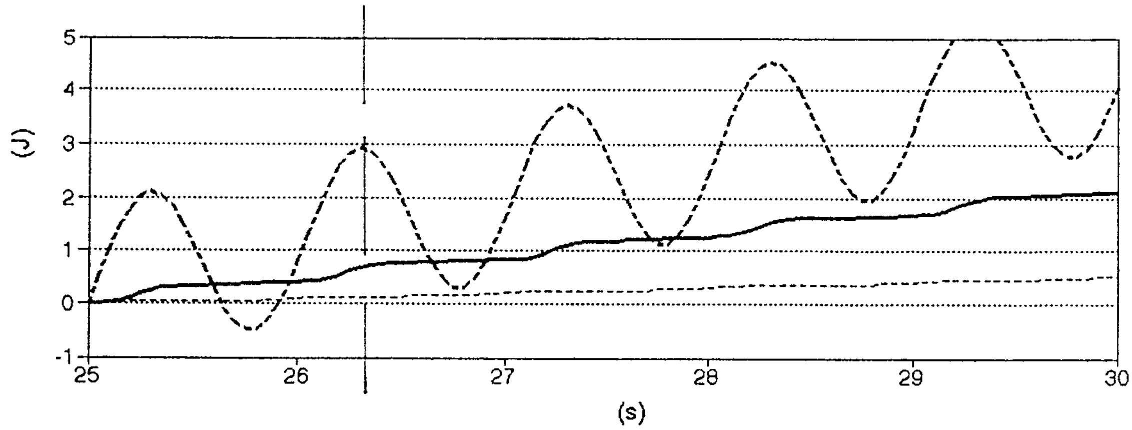

Figure 5. Absorbed energy without phase control (lower broken curve), with latching phase control (fully drawn curve) and with theoretically ideal optimum control (broken wavy curve). The curves show the wave energy (in joule) accumulated during 5 seconds.

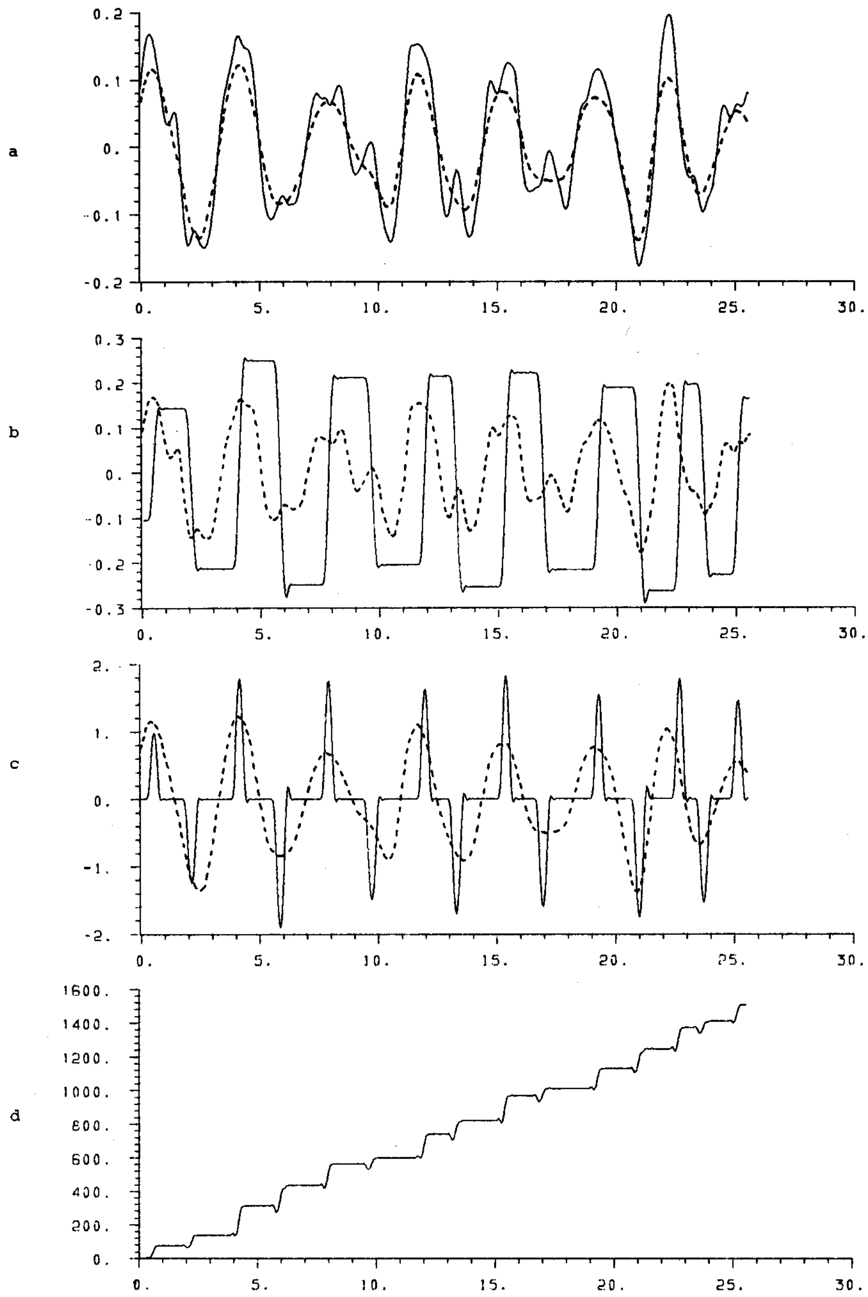

Figure 6. Measurements during 25 seconds of an experimental run with a latching-controlled heaving buoy in an irregular incident wave.[15]

a. *Two different measurements of the wave abreast the buoy.*
Fully drawn line: Surface elevation (in m*) measured by a two-wire probe.*
Dotted line: Hydrodynamic pressure (in 10^4 N/m^2*) measured by a pressure transducer placed* 0.70 m *below the mean water surface.*

b. *Wave elevation and heave position (both in* m*).*

c. *Hydrodynamic pressure (in* 10^3 N/m^2*) and heave velocity (in* m/s*).*

d. *Energy input to piston pump (in* J*). The average slope of the curve corresponds to a power input* 60 W.

With the results shown in figure 6, the average period of the irregular wave is at least 3 s, and thus significantly longer than the natural period. It seems that latching and unlatching occur roughly at right instants, although figure 6b indicates that the latchings occurring at times 6 and 21 s are slightly too late. Figure 6c reveals that the velocity had maximum slightly before the wave at 2 and 9 s and slightly after at 12 and 22 s. This indicates slight inaccuracy in some of the unlatching instants. Figure 6d shows how the accumulated energy is built up when the body moves with proper phase. By and large, a successful phase control was obtained in the experiment.

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