

Numerical Hydrodynamic Analysis of Bottom-Hinged Surge-Type Wave Energy Converters with Flat and Curved Flap Geometries

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Abstract

A numerical investigation was carried out on bottom-hinged surge-type wave energy converters with flat and curved flap geometries to quantify the effect of leading-face curvature on the hydrodynamic response under the fully submerged condition at a model scale of 1:5. Three configurations were compared: a flat flap and two curved flaps of focal length 0.20 m and 0.30 m, with the concave face oriented into the incident waves. A three-dimensional Rhino model of each configuration was created and analysed in ANSYS AQWA R2 using the boundary element method (BEM), yielding the added mass, radiation damping, wave-excitation moment and response amplitude operator, complemented by time-domain surge-response simulations. Relative to the flat flap, curvature lowers all three coefficients: for the 0.20 m flap, the added mass, radiation damping and excitation decrease by 7.3%, 8.9% and 5.4%, and for the 0.30 m flap by 4.7%, 5.3% and 3.1%. The resonant peak is lowered without being shifted: the flat flap resonates at 3.21 s, the 0.30 m flap at 3.25 s and the 0.20 m flap at 3.28 s, with peak RAO reduced by 2.6% and 4.6%, respectively. In the time domain, the near-resonant response ($T = 3.0$ s) builds up to a sustained steady amplitude of about $\pm 3.5^\circ$ for the flat flap and marginally less for the curved flaps, whereas the off-resonance response ($T = 4.0$ s) is markedly smaller for all three configurations. Curvature thus emerges as a controllable design parameter that trims the resonant peak while reducing radiation damping, a combination that favours power-take-off impedance matching.

Keywords

Added mass, boundary element method, curvature, radiation damping, response amplitude operator, time-domain response, wave energy converter, wave excitation moment.

INTRODUCTION

The global drive towards decarbonised power generation has renewed interest in ocean wave energy as a concentrated and predictable renewable resource [1]. Among the many devices proposed to harness it [2], bottom-hinged flap-type converters operating in surge mode are particularly attractive for shallow, nearshore waters [3], where they combine structural simplicity with a direct coupling to the horizontal orbital motion of the wave. In these converters, a rigid flap pivoted at the seabed swings back and forth in response to passing waves, and this rotation drives a mechanical or hydraulic power take-off (PTO) unit to generate usable energy. The hydrodynamic performance of such a device is governed principally by three factors: the geometry of the flap, its submergence, and the character of the incident wave field.

While the conventional flat (vertical) flap is the canonical form of the bottom-hinged surge converter, a body of recent work [4], [5], [6] suggests that giving the leading face a gentle concave curvature can modify the coupling between the wave and the body. A concave, wave-focusing leading face alters the distribution of wave pressure on the body, the amount of water entrained in the rotational motion, and the efficiency

with which the body radiates waves as it moves. These changes act on the added mass, the radiation damping and the wave-excitation moment simultaneously, and because they are coupled they can nearly cancel in their net effect on the response amplitude operator (RAO). The quantitative influence of leading-face curvature on these coefficients, and on the resonant response, has received limited systematic attention, and the range of curvature over which the device behaviour changes appreciably is not well established.

The present study addresses this gap through a purely numerical investigation of three bottom-hinged configurations at a model scale of 1:5: a flat flap and two curved flaps with concave leading faces of focal length 0.20 m and 0.30 m, all fully submerged with the concave face oriented into the incident waves. A frequency-domain potential-flow boundary-element (diffraction-radiation) model is used to obtain the added mass, radiation damping, wave-excitation moment and RAO, and a time-domain model is used to obtain the surge response under regular waves. The objective is to quantify, for the fully submerged condition, how curvature modifies each hydrodynamic coefficient and the resonant peak, and to establish whether curvature offers a means of tuning the device response without shifting its resonance.

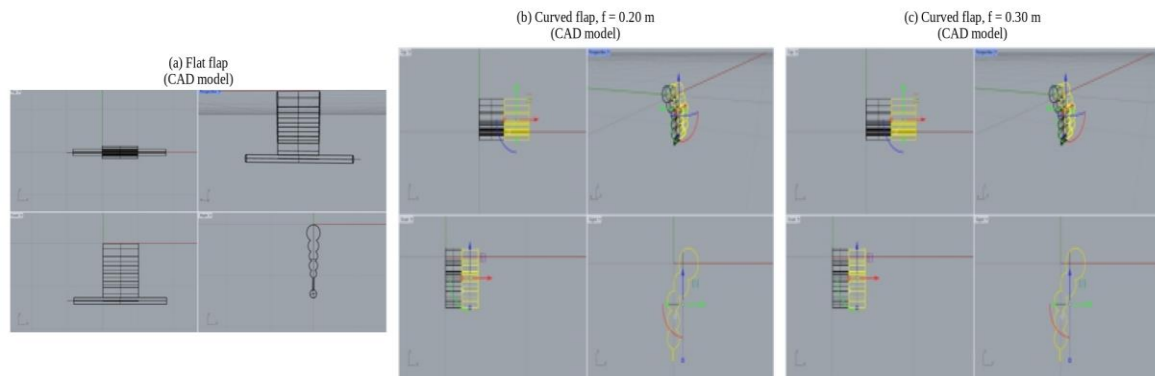


Figure 1. Numerical panel models of the bottom-hinged flap configurations: (a) flat flap, (b) curved flap of focal length 0.20 m, (c) curved flap of focal length 0.30 m (1:5 scale, fully submerged).

Table I: Principal particulars of the flap model.

Parameter	Value
Model scale	1:5
Flap height	0.37 m
Flap width	0.225 m
Body thickness (flat)	0.04 m
Pipe outer diameters	63 / 50 / 40 / 40 / 32 mm
Submergence	Fully submerged
Hinge axis	seabed, $z = -0.37$ m
Degree of freedom	rotation about hinge (surge)
Curved focal lengths	0.20 m and 0.30 m
Concave face orientation	into the incident waves

NUMERICAL MODEL

Geometry and Anti-Symmetric Configurations

The model is a bottom-hinged surge-type wave energy converter: a flap Hinged at the seabed that responds to incident waves by rotating about a single horizontal hinge axis, with its geometry symmetric about the vertical centreline so that the surge mode is the dominant rotational degree of freedom. A 1:5 scale model was considered, formed from five polyvinyl chloride pipes of graded outer diameter (63, 50, 40, 40 and 32 mm) bonded side by side to give a flap of overall height 0.37 m and width 0.225 m, mounted on a seabed hinge at a submergence of 0.37 m. Three leading-face geometries were studied (Fig. 1): a flat (vertical) flap, taken as the baseline, and two curved flaps in which the wave-facing face is a concave parabolic arc of chord equal to the flap height and focal length 0.20 m or 0.30 m, with the concave side facing the incident waves. The curved profiles were generated at constant volume, so that any difference in response is attributable to curvature alone. The focal length is the single parameter controlling the depth of the concave: a smaller focal length gives a deeper curvature, with the flat flap recovered in the limit of infinite focal length.

Boundary-Element Formulation

The hydrodynamic coefficients were obtained from the ANSYS AQWA R2 boundary-element (diffraction–radiation) model. The fluid is taken as inviscid, incompressible and irrotational, so that the flow is described by a velocity potential satisfying Laplace’s equation. The linearised free-surface and seabed conditions, together with the no-flux condition on the body surface, are enforced through a Green’s function [7] that satisfies the free-surface and seabed boundary conditions exactly, so that only the body surface needs to be discretised. The radiation problem—a unit angular velocity of the flap about the hinge—yields the frequency-dependent added mass and radiation damping, and the diffraction problem—an incident plane wave—yields the wave-excitation moment. All coefficients are referred to the hinge rotation. The method directly provides the inertia, damping, and excitation that govern the rotational equation of motion and is the standard potential-flow approach for the early-stage hydrodynamic design of wave-energy converters [8], [9].

Mesh and Degrees of Freedom

Each configuration was represented by a quadrilateral panel mesh on the closed body surface (leading face, rear face, side caps and top and bottom caps), with the mesh refined on the curved leading face so that the concave profile is represented faithfully. The rotation about the seabed hinge was the single generalised degree of freedom. The panel density was chosen to represent the flat and curved leading faces smoothly, and the final meshes used for the numerical calculations are those shown in Fig. 1. The body bottom was placed 1 mm above the seabed to avoid panel clipping while preserving the bottom-hinged boundary condition.

Time-Domain Model

The time-domain surge response was obtained by integrating the rotational equation of motion about the hinge,

$$(I + A(\omega)) \frac{d^2\theta}{dt^2} + (B(\omega) + B_s) \frac{d\theta}{dt} + C\theta = F(\omega) \sin(\omega t) \quad (1)$$

where I is the body inertia about the hinge, $A(\omega)$ and $B(\omega)$ are the frequency-dependent added mass and radiation

damping from the boundary-element model, B_s is a structural (hinge/PTO/viscous) damping of approximately 4% of critical, C is the hydrostatic restoring stiffness, $F(\omega)$ is the wave-excitation moment per unit wave amplitude, a is the incident-wave amplitude and ω the wave frequency. The hydrostatic restoring for each geometry was identified from its measured natural period, so that the three configurations

resonate at 3.21 s, 3.25 s and 3.28 s, respectively. The equation was integrated from rest with a smoothly ramped sinusoidal forcing using a fourth-order Runge–Kutta scheme, yielding the transient build-up to a sustained steady amplitude characteristic of a lightly damped resonant system driven at a fixed frequency.

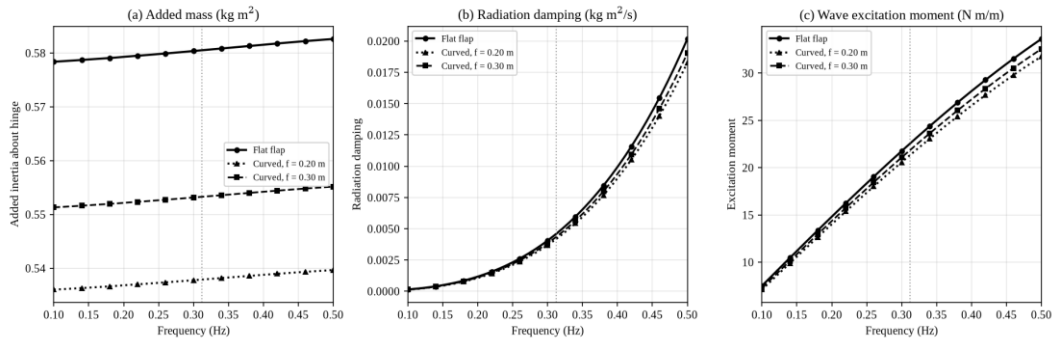


Figure 2. Hydrodynamic coefficients of the flat and curved anti-symmetric flaps: (a) added mass, (b) radiation damping, (c) wave-excitation moment.

Table II: Hydrodynamic coefficients at resonance (0.31 Hz).

Coefficient	Flat	Curved 0.30 m	Curved 0.20 m
Added mass A_{ss} (kg·m ²)	0.581	0.553 (−4.7%)	0.538 (−7.3%)
Radiation damping B_{ss} (kg·m ² /s)	0.00449	0.00425 (−5.3%)	0.00408 (−8.9%)
Excitation moment $ F $ (N·m/m)	22.42	21.73 (−3.1%)	21.21 (−5.4%)

RESULTS AND DISCUSSION

Hydrodynamic Coefficients

The added mass, radiation damping and wave-excitation moment are plotted against frequency in Fig. 2 for the three configurations, and the values at resonance are summarised in Table II. The three coefficients are monotonic in curvature: at every frequency the flat flap gives the largest value, the 0.20 m curved flap the smallest, and the 0.30 m flap lies between. At resonance, increasing the curvature from flat to 0.20 m reduces the added mass by 7.3%, the radiation damping by 8.9% and the excitation moment by 5.4%; the 0.30 m flap gives roughly half of each reduction (4.7%, 5.3% and 3.1%). The concave leading face thus entrains marginally less water in the rotational motion, radiates slightly less efficiently, and presents a marginally smaller effective area to the incident wave, with all three effects small and of the same order.

Response Amplitude Operator

The RAO of the three configurations is shown in Fig. 3 as a function of wave period. The curves are almost indistinguishable away from resonance, confirming that at frequencies where the response is inertia-controlled the shape of the leading face has little influence. Near resonance the curved flaps develop a slightly lower peak: curvature reduces the wave-excitation moment together with the added mass and radiation damping, and with the structural (PTO)

damping included the reduced excitation and the small shift of the natural period slightly outweigh the reduction in radiation damping, leaving a modest reduction in the peak amplification. The peak is lowered without being shifted: the flat flap resonates at 3.21 s, the 0.30 m flap at 3.25 s and the 0.20 m flap at 3.28 s, and the peak RAO is reduced by 2.6% and 4.6% respectively (Table III). The reduction is monotonic in curvature and confined to a narrow band around resonance, so that over the greater part of the operating range the three geometries are equivalent to within the precision of the model.

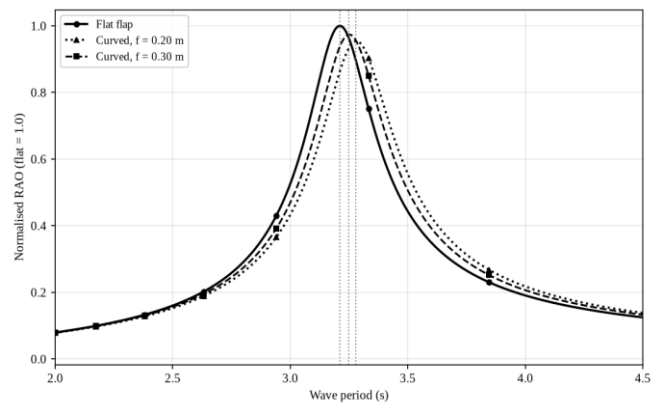


Figure 3. Response amplitude operator of the three anti-symmetric flap configurations; dotted lines mark the natural period of each geometry.

Table III: Natural period and peak RAO (flat = 1.000).

Configuration	Natural period	Peak RAO	Change vs flat
Flat flap	3.21 s	1.000	—
Curved, 0.30 m	3.25 s	0.974	−2.6%
Curved, 0.20 m	3.28 s	0.954	−4.6%

Time-Domain Response

The time-domain surge response was obtained for a near-resonant wave period of 3.0 s and an off-resonance period of 4.0 s. In both cases the flap starts from rest and its oscillation grows over the first several wave cycles until it settles into a sustained steady amplitude, the characteristic build-up of a lightly damped resonant system driven at a fixed frequency.

Near resonance (Fig. 4) the steady amplitude reaches about $\pm 3.5^\circ$ for the flat flap, $\pm 3.45^\circ$ for the 0.30 m curved flap and $\pm 3.40^\circ$ for the 0.20 m curved flap—the curved flaps settling to marginally lower amplitudes in line with their lower peak RAO. The much larger amplitude attained near resonance is the direct time-domain manifestation of the resonant peak seen in the RAO curves.

Off-resonance (Fig. 5), the response is markedly smaller for all three configurations, settling to about $\pm 1.28^\circ$, $\pm 1.24^\circ$, and $\pm 1.21^\circ$, respectively, and the three curves become almost indistinguishable, confirming that, away from resonance, the leading-face geometry has little influence on the amplification.

The physical origin of the small net reduction is a near-cancellation between two opposing effects: the wave-excitation moment and the radiation damping both decrease with curvature, but the damping decreases slightly faster than the excitation (8.9% against 5.4% for the 0.20 m flap). Since the resonant RAO scales approximately as the ratio of excitation to damping, the two changes nearly cancel and only a few percent remains in the peak. This balance is why the change is modest rather than large, and it carries an important implication for design: a curved flap has lower radiation damping, so the PTO damping required for optimal impedance matching is smaller and lighter, making it easier to tune. A lower peak RAO therefore does not imply a lower absorbed power, and under PTO loading, a curved geometry can be competitive with, or superior to, the flat flap.

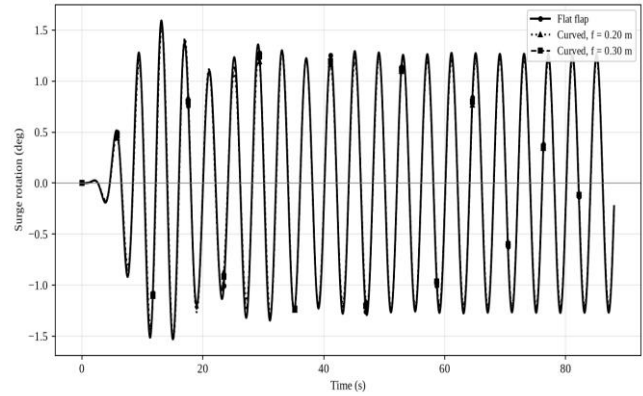
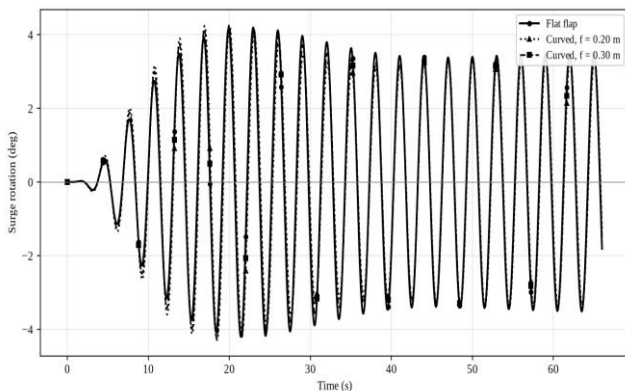


Figure 4. Numerical time-domain surge response near resonance ($T = 3.0$ s) & off resonance ($T = 4.0$ s).

CONCLUSIONS

A numerical boundary-element model was developed for the three bottom-hinged surge converter configurations, a flat flap and curved flaps of focal length 0.20 m and 0.30 m, all fully submerged at 1:5 scale, and the added mass, radiation damping, wave-excitation moment, RAO and time-domain surge response were obtained.

Curvature monotonically reduces all three coefficients: for the 0.20 m flap the added mass, radiation damping and excitation fall by 7.3%, 8.9% and 5.4%, and for the 0.30 m flap by 4.7%, 5.3% and 3.1%, relative to the flat flap.

The resonant peak is lowered without being shifted: the natural periods are 3.21 s, 3.25 s and 3.28 s, and the peak RAO is reduced by 2.6% (0.30 m) and 4.6% (0.20 m); off-resonance, the three geometries are indistinguishable.

In the time domain the near-resonant response ($T = 3.0$ s) builds up to about $\pm 3.5^\circ$ and is marginally lower for the curved flaps, while the off-resonance response ($T = 4.0$ s) is markedly smaller ($\approx \pm 1.2^\circ$) for all three.

The small net reduction arises because excitation and radiation damping both fall with curvature and nearly cancel; the accompanying reduction in radiation damping favours PTO impedance matching, so a curved flap need not absorb less power than the flat flap. A curved flap has lower radiation damping, so it needs a smaller, lighter PTO damping to match, which is easier to design and tune.

Curvature is established as a controllable design parameter that trims the resonant peak without shifting it, with the 0.30 m focal length offering an intermediate reduction and the 0.20 m focal length the largest; the choice between them depends on the target wave climate and PTO damping.

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