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Experimental determination of the hydrodynamic forces responsible for wave impact events

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ABSTRACT

Breaking waves can impose enormous forces on intertidal plants and animals. While some hydrodynamic forces (drag, lift, and the acceleration reaction) are well-studied, the factors affecting the magnitude of a fourth force – the impingement force – remain unknown. Characterized by a sharp, transient spike in force at the instant of wave arrival, impingement is often the largest hydrodynamic force imposed on intertidal organisms, yet the variables affecting its magnitude are unstudied. To delineate the factors influencing impingement, we tested a variety of objects (encompassing a range of areas, volumes, and drag coefficients) in simulated waves using a high-speed water flume. Impingement magnitude is proportional to objects' frontal area and drag coefficient, and occurs concomitantly with spikes in water velocity at the front of simulated waves. We conclude that impingement is a brief spike in drag caused by an increase in velocity at the wave front, rather than a novel hydrodynamic force. Consequently, previous hypotheses regarding impingement's ability to limit organism size in the intertidal zone are rejected.

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1. Introduction

The intertidal zone of rocky shores is one of the most physically stressful environments on Earth, in large part due to breaking waves crashing ashore. Hydrodynamic forces imposed by these turbulent bores have cascading effects that structure surf-zone communities by dislodging organisms (e.g., Bell and Gosline, 1997; Dayton, 1971; Denny, 1987, 1995; Denny and Blanchette, 2000; Denny et al., 1985; Koehl, 1984; Lau and Martinez, 2003; Paine and Levin, 1981; Sousa, 1984; Trussell et al., 1993) and influencing species interactions (e.g., Branch et al., 2010; Lewis, 1964, 1968; McQuaid and Branch, 1985; Paine, 1979; Paine and Levin, 1981; Ricketts et al., 1985; Rius and McQuaid, 2006, 2009; Tam and Scrosati, 2014). Hydrodynamic forces also impact the intertidal food chain: dislodged organisms are food for other organisms (Gaylord, 2007), and large waves discourage predator and grazer movement (e.g., Jenkins and Hartnoll, 2001; Menge, 1978a,1978b). Because of the critical role hydrodynamic forces play in shaping intertidal communities, it is essential that we understand the fluid-dynamic mechanisms that drive these processes. While the parameters controlling the magnitudes of the classical hydrodynamic forces – lift, drag, and the acceleration reaction – are well understood, the variables that determine the magnitude of a purported fourth force – impingement – remain unknown.

Impingement is the sharp, transient spike in force occurring in the first fraction of a second after a wave impacts an emersed object (Fig. 1). Gaylord (1999, 2000) and Gaylord et al. (2001) proposed that impingement is a novel hydrodynamic force that arises when a wave strikes an exposed organism with no surrounding fluid to absorb some of the impact. Their measurements suggest that impingement is the largest force imposed on intertidal organisms, with an average magnitude twice that of drag (Gaylord, 2000).

Our goal in this study is to elucidate the mechanisms underlying impingement. To that end we begin with a review of the classical in-line hydrodynamic forces: drag and the acceleration reaction. In the high-speed flows on wave-washed shores, inertial forces are much larger than viscous forces, and drag, F_D, is a function of fluid density, ρ, organism shape (indexed by the dimensionless drag coefficient C_D), the velocity of the fluid relative to the organism, u_r, and the projected area of the organism exposed to flow, A_{pr} (equivalent to the area of the shadow created by light shining in the direction of flow). Drag can be modeled (Denny, 1988; Vogel, 1994) as:

$$F_D = \frac{1}{2}\rho C_D u_r^2 A_{pr} \tag{1}$$

Blunt objects have a high drag coefficient; sleek ones a low C_D. Though total drag is caused by both viscous friction (produced by the shearing of fluid as it moves past an object's surface) and the pressure difference between the upstream face of an object and the downstream wake, drag due to pressure dominates for all but the most streamlined intertidal objects (Denny, 1988).

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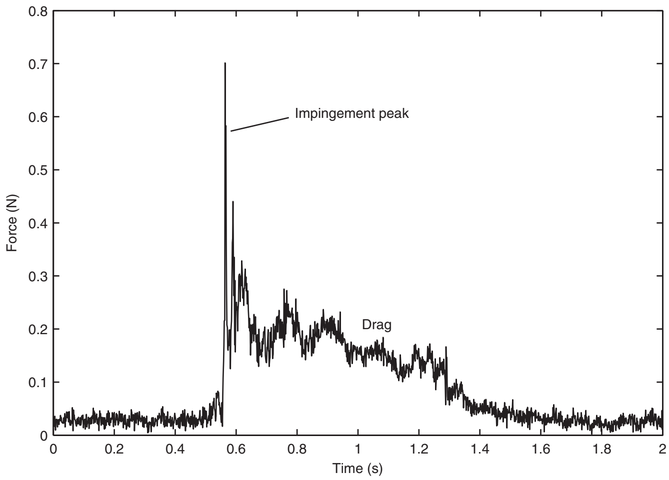

Fig. 1. Magnitude of hydrodynamic force over time as a wave flows past an emersed object, including an impingement event.

In contrast to drag, the acceleration reaction, F_A, scales with the acceleration of the fluid, a, and object volume, V, rather than area, A_{pr}. For a stationary object in accelerating flow, the acceleration reaction can be modeled as:

$$F_A = \varrho C_M V a \quad (2)$$

where ϱ is fluid density, and C_M is the dimensionless inertia coefficient, which takes into account the object's added mass and the virtual buoyancy associated with accelerating flow (Denny, 1988).

To more completely understand the hydrodynamic forces imposed on intertidal organisms, it is necessary to develop a similar model for impingement. In particular, it will be valuable to know whether impingement scales with area or volume. Denny et al. (1985) hypothesized that hydrodynamic forces due to breaking waves may be responsible for limiting organism size. Indeed, organisms living in the intertidal zone are typically smaller than subtidal and terrestrial organisms, and for some species, size varies with wave exposure: in general, large seaweeds, mussels, and starfish are found in protected environments, while smaller individuals inhabit more exposed places (e.g. Connell, 1972; Harger, 1970, 1972; Paine, 1976a,1976b; Schwenke, 1971).

An organism's ability to resist hydrodynamic force is dependent on its strength, which typically varies with the cross-sectional area of the organism's most vulnerable structure (Denny et al., 1985). If an organism grows isometrically, this cross-sectional area increases at the same rate as projected area as the organism matures. Consequently, strength increases hand in hand with drag, and drag therefore has no capacity to limit the organism's size. By contrast, the acceleration reaction increases with an organism's volume, and therefore it increases at a faster rate than strength. Thus, when an acceleration reaction is imposed there can be a critical length at which the organism exceeds its attachment strength.

However, volume-scaling accelerational forces are not likely to limit organism size: though large accelerations have been measured in the intertidal zone, their small spatial scales (on the order of one centimeter) result in a lack of uniform acceleration preventing large accelerational forces from acting on large organisms (Gaylord, 2000). Small organisms lack the necessary volume to generate large accelerational forces.

Though drag and accelerational forces apparently do not pose an intrinsic limit to organism size, the scaling behavior of impingement has not been measured. If impingement scales with volume, it could potentially provide a size-limiting mechanism.

To determine whether impingement scales with object area or volume, we tested a variety of objects comprising a range of areas, volumes, and drag coefficients in simulated waves. We explored the relationships between these variables and impingement magnitude to describe the mechanics behind what may be controlling hydrodynamic events in the intertidal zone.

2. Methods and materials

2.1. Wave simulation

Controlled, repeatable waves were simulated using a gravity-driven water flume. This apparatus consists of a large (approximately 8 m tall) vertical pipe with a 10.2 cm internal diameter in which water is accelerated by gravity, simulating a crashing wave (Fig. 2B). Two pneumatically-operated gate valves control the volume of water in the pipe and the height at which it is released (and thus, the velocity of the jet upon exit). Overflow holes in the pipe control the volume of water from trial to trial. When one of the gate valves is abruptly released, the water falls down the pipe into a wide-radius 90-degree elbow that directs the flow out of the pipe horizontally. Using this apparatus, repeatable simulated waves can be generated (Martone and Denny, 2008; Martone et al., 2012).

Experiments were conducted at three water-jet velocities. A high-velocity jet is created using a valve 3.1 m above the flume outlet, with a 1.6-m column of water in the pipe above the valve. A second, lower valve 0.8 m above the jet outlet can support columns of water either 2.2 m or 0.7 m high, which produce medium- and low-velocity jets, respectively.

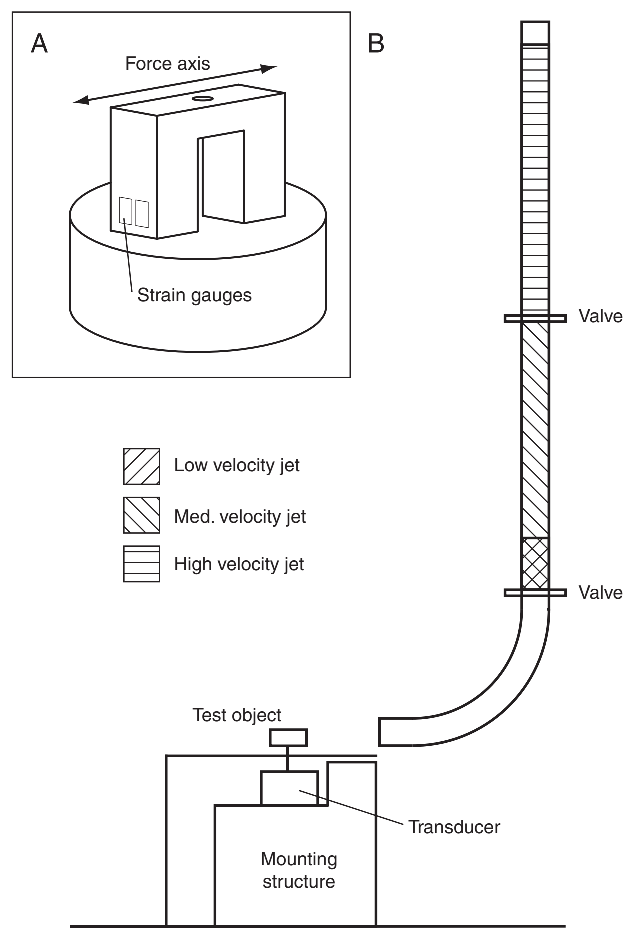

Fig. 2. A) Diagram of force transducer. B) Schematic of gravity-driven water flume, showing valve locations and relative volumes of water released at each of the three velocities.

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