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Multi-objective optimization and scenario-based robustness analysis of the MoneyMaker Hip Pump

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ABSTRACT

Water-lifting technologies for irrigation have significant potential to increase agricultural yields and stimulate economic growth in rural areas of the developing world. Human-powered water pumps have been used with great success in this rapidly developing market. KickStart's MoneyMaker Hip Pump is a human-powered water pump with additional design features that make it lightweight and portable for use in remote fields in several countries throughout Africa. This work first applied numerical optimization techniques to the design of the MoneyMaker Hip Pump and offers further improvements to its design. Deterministic multi-objective optimization methods were employed to maximize the flow rate of the pump, maximize the pumping height of water, and minimize cost. Following optimization, the robustness of the optimized pump design was analyzed under several modified scenarios, including fouling of the hoses and a decrease in operator power due to fatigue or aging. The set of cost-optimized pump designs was then compared to a second set of optimal designs that was found using material volume as a simplified proxy for the cost objective function. Findings indicate that several technical improvements can be made to the current MoneyMaker Hip Pump design to reduce cost by up to 37% without affecting water flow rate, or increase water flow rate by up to 88% without increasing cost. The numerical model was validated through physical experimentation of the MoneyMaker Hip Pump, and design alterations to reduce cost were experimentally shown to maintain pump performance.

1. Introduction

Rural villages in developing countries face many hardships, including a lack of basic infrastructure, insufficient health care facilities, limited educational opportunities, little access to clean water and energy, long workdays completing household tasks, and sparse opportunities for entrepreneurship and economic growth (Bolay et al., 2014; Johnson and Bryden, 2012, 2013). Governmental and non-governmental organizations have provided significant financial and material aid over the last sixty years, but the extent of poverty in rural areas has remained largely unchanged (Polak and Warwick, 2013). In contrast to traditional humanitarian aid in which governments and large organizations act as intermediaries, market-based approaches seek to increase economic activity in developing countries via entrepreneurship. Market-based strategies can be more effective than traditional aid because they use a bottom-up approach to boost local business development and increase individual income (Cooney and Williams Shanks, 2010).

Many development organizations target the agricultural sector of developing countries because subsistence agriculture or small-scale farming is the primary occupation in rural areas (Magistro et al., 2004). Reliable irrigation techniques have been shown to increase crop yields by at least 100% and at most 400% (Food and Agriculture Organization of the United Nations, 2000). The resulting increase in crop yield translates to increased sales and income, and can allow farmers to cultivate higher-value crops and adopt new technologies. The rise in income allows farmers to expand arable land and further increase production and income each season. This incremental, yet significant, improvement is attainable without conventional pumping techniques

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that require substantial financial investment relative to income. For instance, diesel pumps are effective for irrigation but the capital cost and fuel costs prohibit use by many subsistence farmers (Polak, Nanes, Sample).

Human-powered pumps are a popular option for farmers with small plots of land given the low capital cost and operating cost (International Development Enterprises - Nepal, 2011). Perhaps the most ubiquitous of these is the foot-powered treadle pump, invented by the Norwegian engineer Gunnar Barnes in the 1970s (Bolay et al., 2014) and first introduced in Bangladesh (Orr et al., 1991). Since the inception of the treadle pump, companies such as International Development Enterprises (IDE) and KickStart have re-designed the treadle pump and introduced a variety of other human-powered pumps. Current treadle pump designs can draw water from depths reaching 7 m at flow rates up to 5 L/s (Orr et al., 1991; Bielenberg and Allen, 1995). Human-powered pumps have helped numerous subsistence farmers transition out of poverty (Polak and Yoder, 2006; Shah et al., 2000; Mangisoni, 2008; Fisher, 2006).

The basic treadle design was modified by KickStart to meet consumer demands for portability and to permit hand operation instead of foot operation (Sijali et al., 2011). The resulting MoneyMaker Hip Pump (see Fig. 1) has a suction lift of 7 m. The pump is also capable of delivering water with a head of up to 7 m, but the typical use case is usually closer to 3 m (KickStart, 2009).

Human-powered pumps are an effective irrigation solution for many subsistence farmers but problems have been observed during deployment. For instance, from 1995 to 2005 treadle pumps were freely distributed to farmers in Malawi. However, 60% of the pumps were not put to use (Chidanti-Malunga, 2009). Evidence suggests that the scarcity of spare parts and lack of well-organized markets restricted adoption (Mangisoni, 2008). Studies have also indicated that adoption might be improved through modifying the socio-economic system in which pumps are distributed and operated (Mangisoni, 2008; Kamwamba-Mtethiwa et al., 2012).

Data suggests that treadle pump output is typically small and is independent of the body type of the operator (Chidanti-Malunga and Yamikani, 2011). These performance barriers of human-powered pumps are one factor limiting their adoption. It is also clear that adoption rates are closely related to ease-of-use. Work by Lewis et al. led to the creation of a modular treadle pump design that could be reconfigured with additional components to achieve progressively higher pump performances (Lewis et al., 2010, 2015). In that work, a series of pump designs began with a low-cost module that could be expanded with a higher-performing module once earnings increased as a result of using the basic pump design. Design trade-offs between cost and performance of the treadle pump have been explored through design optimization and engineering analysis but limited studies have been completed for hand-powered pumps (Santaeufemia et al., 2014).

This work developed a volumetric fluid model of the MoneyMaker Hip Pump and applied multi-objective optimization techniques to maximize flow rate, maximize delivery head, and minimize cost. The resulting set of optimized solutions (referred to as a Pareto set) sought to balance the competing objective functions. Optimal pump designs were further analyzed under several scenarios, including fouling of the hoses and decreased operator power through fatigue or aging, to assess the robustness of the optimal designs. Finally, experimental verification of the volumetric fluid model and partial validation of the optimization results was undertaken.

2. The physical system

Design specifications for the MoneyMaker Hip Pump include drawing water from a well up to 7 m deep, transporting the water at ground level through a hose approximately 18 m in length, and pumping water up into a tank of 3 m in height (Kickstart, 2013). Tank placement of 3 m above ground is the typical use case specified by Kickstart and is within the maximum rated water delivery head of 7 m.

Fig. 2 shows the MoneyMaker Hip Pump with all physical dimension variables labeled. The inner and outer diameters of the pump inlet hose were denoted by x_1 and x_2, whereas x_9 and x_{10} denoted the inner and outer diameters of the outlet hose. The inner and outer diameters of the pump cylinder were denoted by x_3 and x_4, respectively. Variables representing inner and outer diameter were constrained according to a regression analysis presented in this work. The length of the piston was denoted by x_8, and the length of the piston's stroke was denoted by x_5. The variables x_6, x_7, x_{11} and x_{12} described the position of the pump relative to the water source and the tank. These were closely related and heavily constrained according to a standard use configuration supplied by Kickstart (2013). The operation of the pump was further described by x_{13} and x_{14} (forces applied during the downstroke and the upstroke) and x_{15} and x_{16} (velocities of the downstroke and the upstroke). Variables x_1 through x_{12} represented lengths and diameters, and were measured in meters (m); x_{13} and x_{14} were forces, measured in Newtons (N); and x_{15} and x_{16} were velocities, measured in meters per second (m/s).

3. Numerical optimization

This work employed numerical optimization techniques to identify technical improvements and cost reductions to the MoneyMaker Hip Pump. Specifically, multi-objective optimization was utilized to examine the effect of the design variables on the conflicting objective functions for flow rate, height of the tank, and projected pump cost. This yielded a set

(a) (b)

Fig. 1. The MoneyMaker Hip Pump (a) as a computer model (Kickstart, 2013), and (b) during use (Kickstart, 2015).

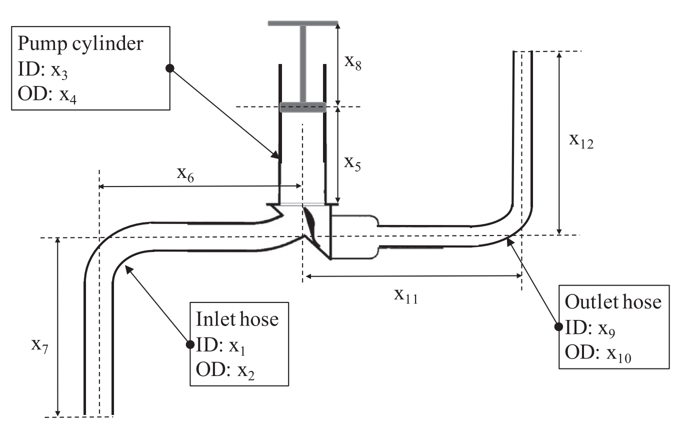

Fig. 2. Design dimensions, forces, and velocities of the MoneyMaker Hip Pump.