Title: Measuring Water Flow Rate in a Flexible Fire Hose using an Accelerometer

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Abstract

A wired sensor network was created to measure water-flow rate in a fire hose. An integrated electronic piezoelectric (IEPE) accelerometer was chosen as the sensor to measure the flow rate based on the vibrations generated by water flowing through a fire hose. These sensors are small, lightweight, and they can attach to the outside of the hose, not obstructing the water's flow path. A relationship was determined between the flow rate of the water and vibration detected by the accelerometer for a range of flow rates. The raw acceleration signal was used to calculate two metrics: the dominant frequency and the standard deviation of acceleration. In a future study, the relationship between the dominant-frequency metric and the flow rate will be applied to a wireless accelerometer network. The relationship will be used to determine real-time, fire hose, flow rate critical for improving situational awareness on the fireground.

Keywords: Accelerometers, fire hose, flow induced vibration, flow rate, hose vibration, dominant frequency, smart firefighting, sensors, water flow rate measurement, wired sensor network.

Introduction

Placing and flowing water through initial, intermediate, and final hose lines is very important for the success of a fire attack. The water discharged from the hose nozzle cools the environment, which improves the survival of trapped occupants, protects the firefighters from excessive heat, and extinguishes the fire. Therefore, hoses are simultaneously a firefighter's and occupant's lifelines [1]. Knowing the water flow rate through a fire hose is a critical part of fire suppression and situational awareness, especially for zero flow conditions, which are not uncommon.

Applying 'smart' technology to a fire hose could improve 1) the awareness of the hose's current status and 2) the chance of a successful fire attack. Harnessing the power of 'smart' technology to improve situational awareness of the hoses was a part of the vision of Smart Fire Fighting as documented in the Research Roadmap for Smart Fire Fighting [2]. A 'smart' system uses sensors to collect data, provides the data in an understandable format to a user, then allows the user to make decisions. Today, the users are humans, but tomorrow they will include software.

Human firefighters are the backbone of the fire service. The safety of firefighters who risk their lives on the fireground could benefit from a smart sensor system that could perform two tasks: determine if water is flowing at the fire-hose nozzle and communicate this information back to a human controller at the fire engine.

Currently, communication between the firefighter at the nozzle and the pump operator or incident commander (IC) is typically done using radios. The firefighter at the nozzle, or his backup, should be able to communicate by radio with the pump operator or IC to provide feedback about water flow. However, this is not always possible due to competing radio traffic and performance of tasks that require two hands such as advancing the hose and conducting suppression activities.

Presently, water pressure measured at the fire engine's pump panel is used by the pump operator to determine if water is flowing at the hose nozzle. Fireground threats to normal water flow such as hose damage and hose blockage can make reliable decisions on water pressure misleading. A pressure loss indicated on the fire engine's pump panel may occur when water flows from the nozzle as intended, or unintentionally through a ruptured hose. A ruptured hose can occur as a result of wear and tear, a burn hole in the hose, a leaking coupling, or from being crushed under a vehicle tire or structure debris.

Sufficient water pressure may show at the pump panel even if the hose is partially or fully blocked preventing water, or allowing too little water, from reaching the nozzle. A charged hose line advanced inside a structure could become partially blocked as a result of being crimped around a sharp corner or past a piece of furniture. A hose pinched under a door, under a piece of furniture, under a vehicle tire, or under fallen debris could also reduce water flow at the nozzle. Water flow through the hose could be fully blocked by a closed in-line valve, debris in the hose, or by a closed nozzle bale that cannot be opened by an incapacitated firefighter.

A reliable way for the IC to know that water is flowing from the hose nozzle is to have real-time water flow information sent to them. The goal of this study is to provide that information digitally by developing a wired sensor network to measure water flow in a fire hose. Our approach, which is detailed below, is to collect vibration data, convert it into a flow rate using a well-known algorithm, then display the flow rate at the incident command post.

Methods

The commercial fire-attack hose used in this study has a nominal 4.5 cm (1.75 in) inner diameter and was approximately 15 m (50 ft) long. The initial flow rate was set in 19 LPM (5 GPM) increments between approximately 0 LPM and 606 LPM (160 GPM). For consistency, the abbreviation 'LPM' represents L/min and 'GPM' represents gallons/min. A commercial turbine flow meter was used at the nozzle to measure the reference flow rate during the study. For a variety of reasons, the reference flow rate drifted approximately ±3.8 LPM (1.0 GPM) at the highest reference flow rates but drifted less than approximately ±1.9 LPM (0.5 GPM) at the lower reference flow rates.

Several different types of flow meters were assessed for use in this study such as: turbine, electromagnetic, and pressure differential meters. However, these types of meters were typically too large, heavy, and bulky for use with the fire hose. Alternatively, a small, lightweight, exterior accelerometer was chosen for the fire hose application. The four piezoelectric accelerometer sensors (PCB model 288D01 and 352C33) communicated over the wired network to the data acquisition system. The sensors, which stand about 2 cm high, were mounted on bases epoxied to the outer surface of the hose (Fig. 1). The four accelerometers were positioned along the hose (Fig. 2) [3]. Vibration data from all four accelerometers was collected for 50 consecutive, 3-second-long test intervals at a sampling frequency of 5 kHz.

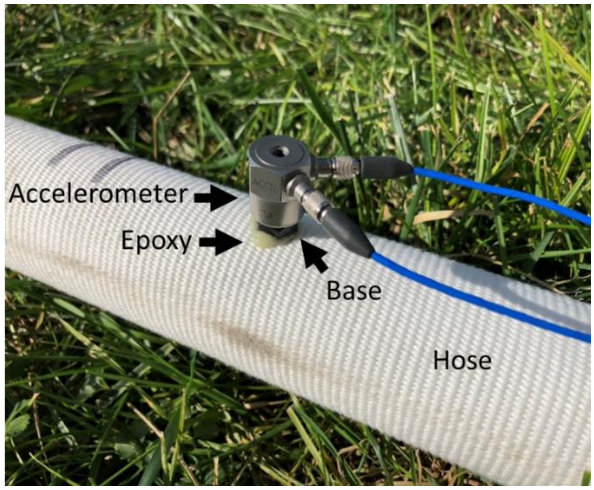

Fig. 1. The accelerometer attached to a base that was epoxied to the exterior fabric of the fire hose at the downstream (Front) location.

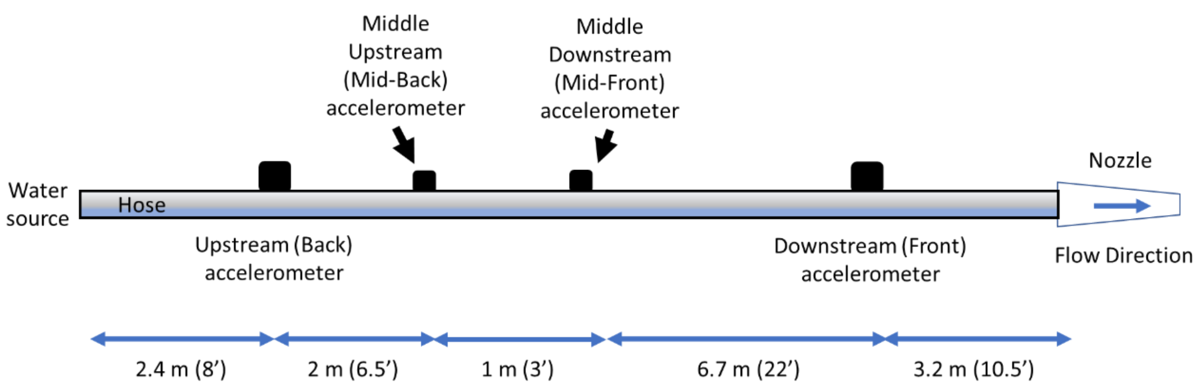

Fig. 2. The four accelerometer locations along the approximately 15 m (50 ft) long fire hose.

Impact testing was done to understand the flexible hose dynamics as well as the dominant frequency of the hose system. An impact hammer was used on the downstream (Front) accelerometer during the following approximate flow rates to determine dominant frequencies: 606 LPM (160 GPM), 454 LPM (120 GPM), 303 LPM (80 GPM), 151 LPM (40 GPM), and 0 LPM. The impact profiles of thirty impacts were collected.

Results and Discussion

The standard deviation of acceleration was calculated from the raw acceleration data and plotted versus flow rate at each of the four accelerometer locations along the hose (Fig. 3). The standard deviation of acceleration generally increased until peaking and then decreased at all four accelerometer locations. The standard deviation values at the front accelerometer location were larger than the values from the other three locations.

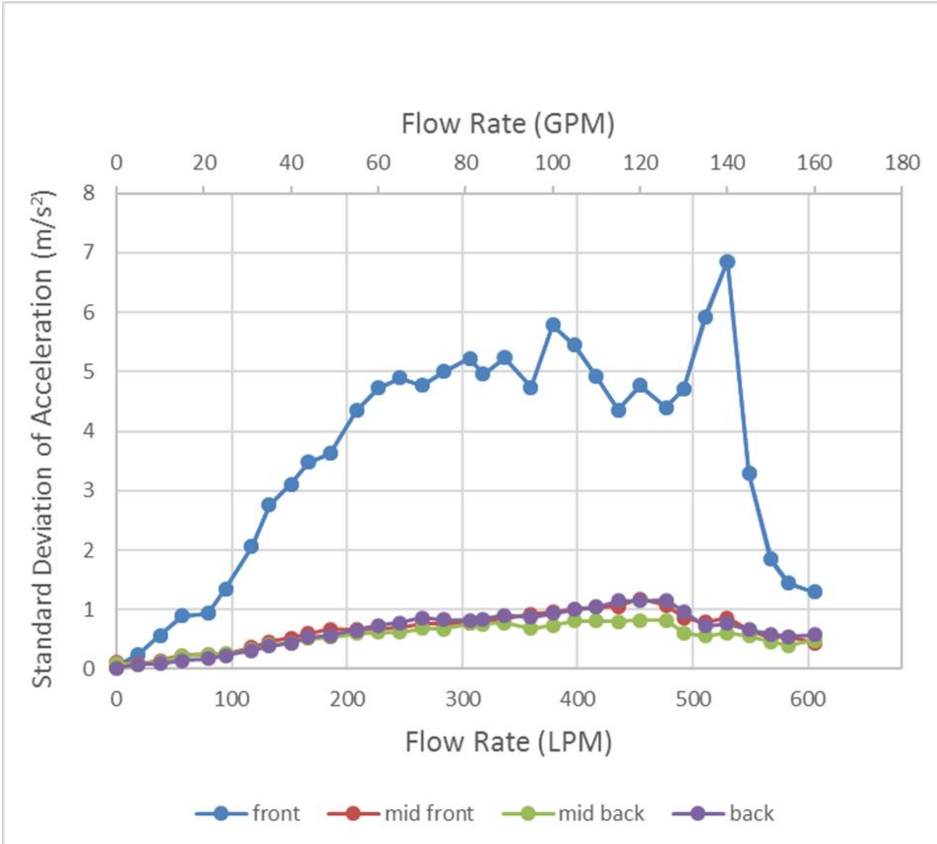

Fig. 3. Typical results of the standard deviation of acceleration versus flow rate for the four accelerometers. Data among the 50 consecutive runs was similar and therefore for visualization purposes only one run was used to represent all the data in the figure.

Based on previous studies using relatively rigid pipe [4-9], a decreasing trend was not expected at the higher flow rates for the flexible hose. The structural dynamic differences between the rigid pipes and the flexible hose could be causing the decreasing trend at higher flow rates although additional research is needed for confirmation. The bell-shaped curve determined at each accelerometer location excludes the standard deviation of acceleration as a metric for determining flow rate over the entire flow range because of the lack of monotonicity; at a single level of standard deviation of acceleration, there are two corresponding flow rates.

The time-domain acceleration data was converted to frequency-domain using a Fast Fourier Transform (FFT). A dominant frequency at each flow rate was observed. A decreasing trend was observed for the front accelerometer only (Fig. 4). When water is flowing through a rigid pipe, the dominant frequency typically does decrease with increasing flow rate [4, 10, 11]. Thus, a similar trend at the front accelerometer was expected for a flexible hose.

To test that hypothesis, we compared the results from two different testing approaches: impact testing and flow-rate testing. The dominant-frequency results as calculated from the impact testing at 5 flow rates were very similar to the results from the flow tests (Fig. 5). This comparison confirmed the determination of the dominant frequency using only the flow tests, and no additional impact testing was needed. What was needed, however, was the ability to determine the real-time flow rate using dominant frequency as a metric. In this paper we show that it was possible to make that determination using only the data from the accelerometer located closest to the hose nozzle.

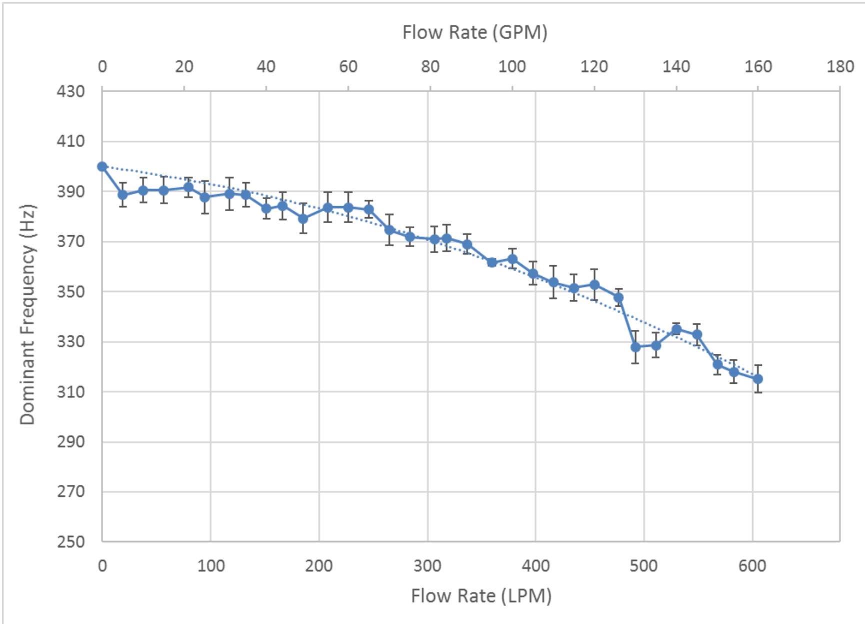

Fig. 4. The mean and standard deviation for the dominant frequency versus flow rate for the Front accelerometer from the flow-rate testing.

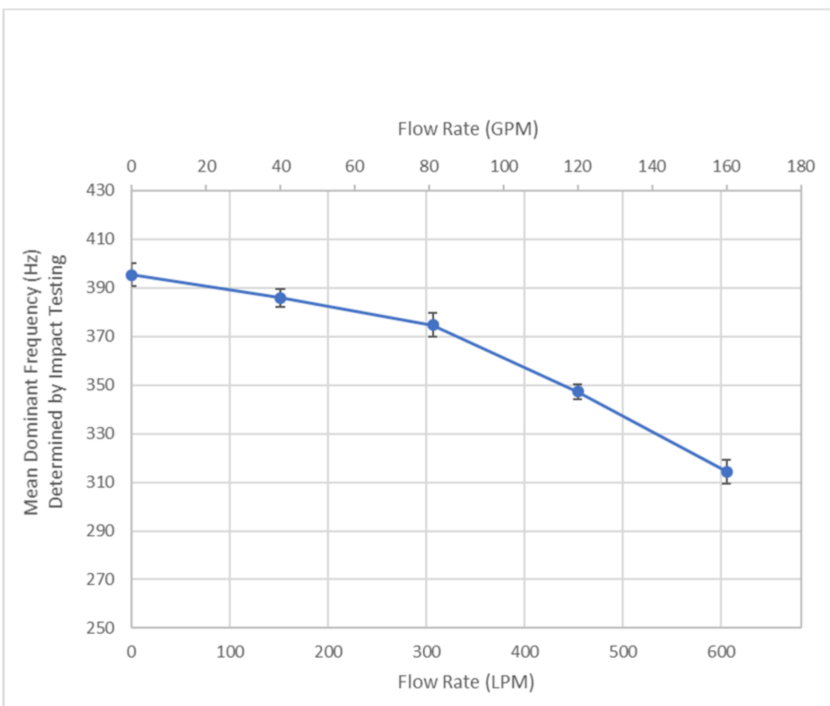

Fig. 5. The mean and standard deviation for the dominant frequency versus flow rate for the Front accelerometer from the impact testing.

Conclusion

The goal of this study was to develop the wired accelerometer as a sensor to determine flow rate near the nozzle of a fire hose. The standard deviation of acceleration and dominant frequency were examined to determine which metric would correlate well with flow rate over the entire flow rate range. The dominant frequency metric yielded a somewhat linear, and generally monotonic, relationship with flow rate for an accelerometer located close to the hose nozzle that can be applied for further study. The next step will be to develop the wired accelerometer system into a wireless sensor network and apply a metric based on dominant frequency and other measures to robustly determine flow rate in a fire hose [12]. The final step will be to use the wireless accelerometer network and finalized metric to determine real-time flow in a fire hose to improve fireground situational awareness.

Acknowledgement and Disclaimer

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