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Innovative Liquid Damper for Wind-Induced Vibration of Buildings: Performance after 4 Years of Operation, and Next Iteration

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Abstract

In 2016, an innovative liquid damper system was installed on the roof of a 35-story modular building in Brooklyn, NY to mitigate wind-induced movement of the structure. The new damper presented several advantages over traditional pendulum, liquid column or sloshing dampers, including lower fabrication and maintenance costs, modularity, and the flexibility to be tuned to a wider range of frequencies. The performance of the system was monitored on a regular basis over the past four years and found adequate, with only minor re-tuning and maintenance operations needed. Based on the experience and data gained through this project, a second iteration of the damper was developed. Called Hummingbird, the improved system further mitigates maintenance and tuning concerns, while allowing significant space savings.

Keywords: Damper, Vibration, Wind, Serviceability

1. Introduction

Tuned mass dampers (TMDs) are commonly used in modern tall buildings to reduce wind-induced vibrations. Most TMDs fall into one of four categories: sliding masses, pendulums, liquid column dampers and sloshing dampers. While each of these systems has proven effective at mitigating movement for different building heights and wind environments, they also each have drawbacks. Sliding masses and pendulums rely on expensive mechanical devices for energy dissipation, which also require maintenance. And the liquid column and sloshing dampers, as water-based systems made of large concrete or steel tanks, have a history of leaking and can only be tuned to a narrow range of frequencies once they are built. When presented with the opportunity to design a TMD for new building that required a relatively small amount of supplemental damping, Thornton Tomasetti developed a different solution that alleviates some of the issues associated with traditional TMDs. The research and development was done in collaboration with the National Aeronautics and Space Administration (NASA), who had studied innovative TMD systems for rockets and made their technology available for licensing through their Spinoff program.

2. Air-Tuned damper development

The innovative TMD developed by Thornton Tomasetti and NASA is referred to as the Air-Tuned Damper (ATD). As shown in Figure 1, the ATD was developed as a series of changes to the traditional tuned liquid column damper (TLCD) system. First, the large U-shaped tank of the TLCD was split into several smaller tanks, to create an array of dampers that can be tuned to different frequencies by adjusting the water level in each tank. To build this array of smaller U-shaped tanks, it was decided to use off-the-shelf plastic pipes as a cheaper alternative to the concrete or steel tanks typically used for TLCDs. The design of the ATD was based on three-foot diameter

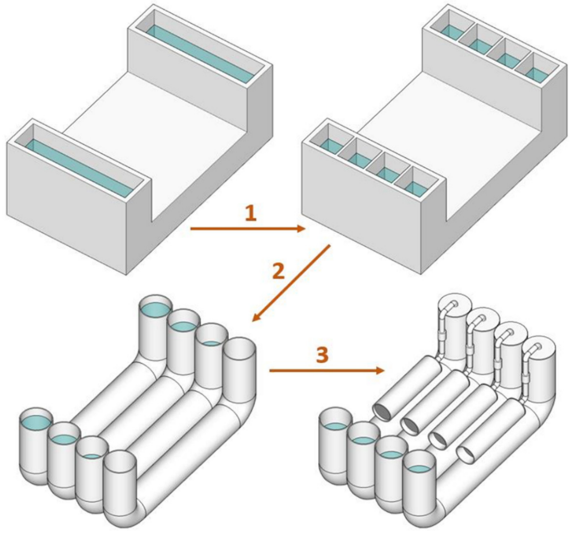


Figure 1. From TLCD to ATD.

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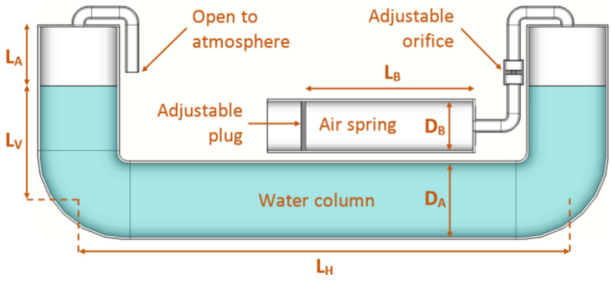


Figure 2. ATD Design Parameters.

corrugated PVC pipes, which are normally used for water mains and sewers.

The next key innovation of the ATD was to add an air spring to each water tank. As shown in Figure 2, the air spring is another PVC pipe connected to one end of the water-filled pipe. As the water moves in the U-shaped tank, the air gets compressed or depressed in the air spring, which induces in a reaction force on the water. The stiffness of the air spring depends on the enclosed volume of air, and this can be set by adjusting the position of a pipe plug in the air spring.

With the design parameters shown in Figure 2, the frequency of the ATD can be calculated with Equation 1, where ρ is the mass density of water, g the gravitational acceleration, P_{atm} the atmospheric pressure and γ the heat capacity ratio of air.

$$f=\frac{1}{2\pi}\sqrt{\frac{2g}{L_H+2L_V}}\sqrt{1+\frac{\gamma P_{atm}D_A^2}{2\rho g(L_A D_A^2+L_B D_B^2)}} \quad (1)$$

The energy dissipated by the ATD is controlled by an adjustable orifice that perturbs the air flow in and out of the air spring.

3. Application to 461 dean street

The ATD system was installed on a 35-story residential building located at 461 Dean Street in Brooklyn, New York. When it topped out in 2016, 461 Dean Street was the tallest modular building in the World. The structure consists of apartment-size prefabricated modules stacked around a braced core and connected to one another. Because of the unprecedented size of the project, the contribution of the modules to the stiffness and damping of the structure was not precisely known before construction, and the results of wind tunnels tests under conservative assumptions recommended to include a TMD to mitigate wind-induced vibrations. Being modular and tunable to a wide range of frequencies, the ATD system was well suited for this application, where the building's properties only became known late during construction. As shown in Figure 3, the design of the ATD system changed significantly over time. The initial design featured ATD units in both translational directions of the building, but the long direction was eliminated after the intrinsic damping of the building was measured to be sufficient in that direction. In the short direction, the size of the air springs was reduced from two pipes to a single pipe after the building frequency was measured to be sufficiently high. Finally, ATD units that were to be placed side-by-side were eventually stacked vertically to make room for a last-minute change in mechanical equipment on the roof.

The ATD units were fabricated in the State of Virginia and transported by truck to the building site in New York. Each unit was hoisted up to the roof in one pick with the building's construction crane. The water, mixed with glycol to prevent freezing in the winter, was finally added.

After taking final measurements of the building's natural frequencies, the ATDs were tuned by positioning the air spring plugs. As shown in Figure 4, the four ATDs were tuned to different frequencies to bracket two modes of vibration that contribute to the short-direction movement of the building: the first short-direction translational mode (0.45 Hz), and the first torsional mode (0.58 Hz). Each ATD can be turned off by closing a valve between the water pipe and the air spring, which considerably stiffens the system and prevents coupling with the building modes. The roof acceleration data presented in Figure 4 was recorded after tuning the ATDs and shows that the building's movement is cut in half when the system is turned on.

4. Performance Monitoring

After the system was commissioned in February 2017, the ATDs on the roof of 461 Dean Street were inspected

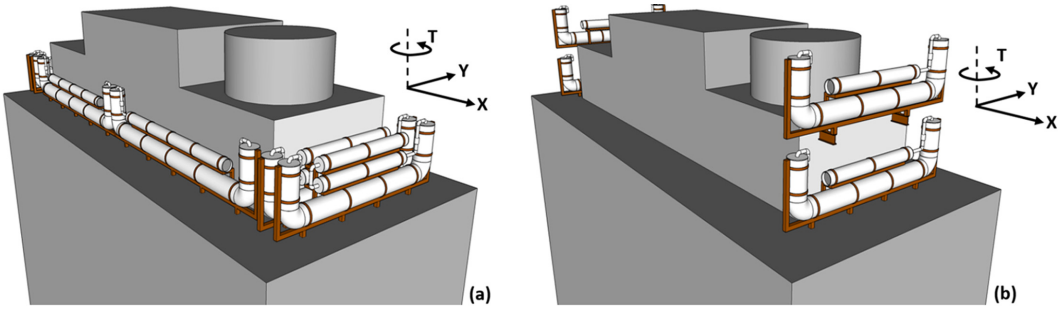


Figure 3. Initial (a) and final (b) ATD design for 461 Dean St.

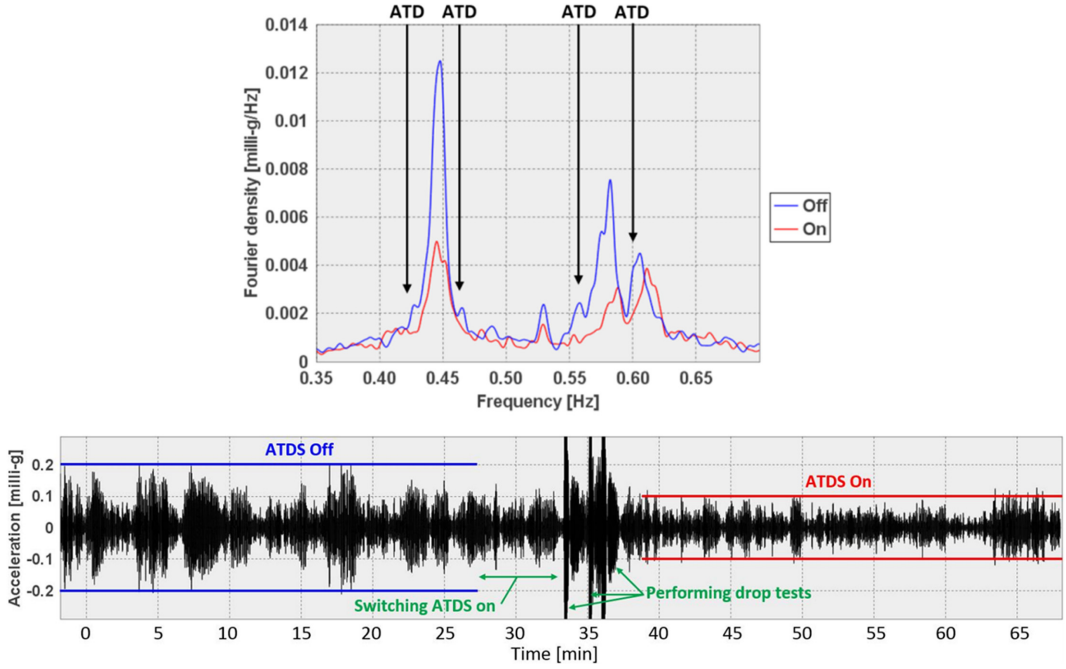


Figure 4. Short-direction acceleration building roof in time and frequency domains with ATD system on and off.

and tested twice a year. The corrugated PVC pipes, coated for UV protection, were found to age well and remain watertight. Because one end of the water pipes is open to the atmosphere (Figure 2), fluctuations of the water level were expected to occur and needed to be monitored to evaluate the impact on the system's performance. When the volume of water changes, the mass and stiffness of the ATD change in different proportions, and therefore the frequency of the ATD also changes. The water levels were monitored indirectly by measuring the frequency of the ATDs during each inspection visit. To measure the frequency of an ATD, the water column is first displaced with compressed air and then suddenly released to initiate movement. Subsequently, the water column oscillates at the natural frequency of the ATD until the movement dies down due to the ATD's damping. The pressure in the air spring experiences the same oscillations as the water column and can be recorded to determine the frequency and damping of the ATD. The frequencies and damping ratios measured in the four ATDs since commissioning are shown in Figure 5. The discontinuities visible in the fall of 2018 and 2019 correspond to re-tuning operations, where water was added back into the ATDs that had lost water. While frequencies and damping ratios fluctuated over the past four years, the system remained effective at mitigating wind-induced movement of the building per the project's requirements.

5. The Hummingbird damper

The ATD installation at 461 Dean Street demonstrates the feasibility of a low-cost, modular and air-tuned liquid damper system made of plastic pipes. Building up on this success, Thornton Tomasetti partnered with Rowan

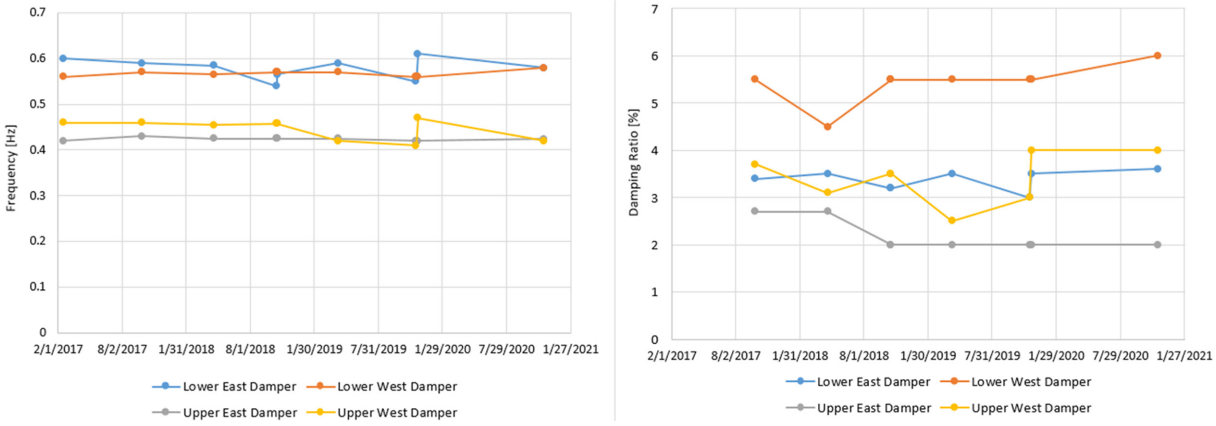


Figure 5. Bi-annual ATD frequency (left) and damping (right) measurements.



Figure 6. Two ATDs on the roof of 461 Dean Street.

Williams Davies & Irwin (RWDI) in 2017 to develop an improved version of the ATD: the Hummingbird damper. One issue with the ATD is that it still uses a U-shaped tank to create a water column, which imposes two limitations. First, the water in the U-shaped pipe is subjected to a gravity-induced stiffness, as the water always goes back to an equilibrium position under gravity. The air spring can add to the gravity stiffness, but it cannot subtract from it. As a result, for any given water mass there is a minimum stiffness and frequency to which an ATD can be tuned. This complicates the application of the ATD to the low frequencies of supertall buildings. Second, the U-shaped pipes do not use space efficiently. Significant height is required to fit the upturned ends of the pipe, while a lot of space remains unused between the upturned ends. To eliminate the U-shaped pipe, the Hummingbird damper separates the water from the air with loose membranes, as shown in Figure 7. The water column, now contained between a pair of membranes, can still flow back and forth in the pipe. An additional benefit of the membranes is that the water column is now a closed system, not opened to the atmosphere and therefore not subject to water volume fluctuations over time. The Hummingbird damper shown in Figure 7 is an all-in-one unit, where the water column and air springs are contained in a single pipe. However, it is also possible to place the air spring

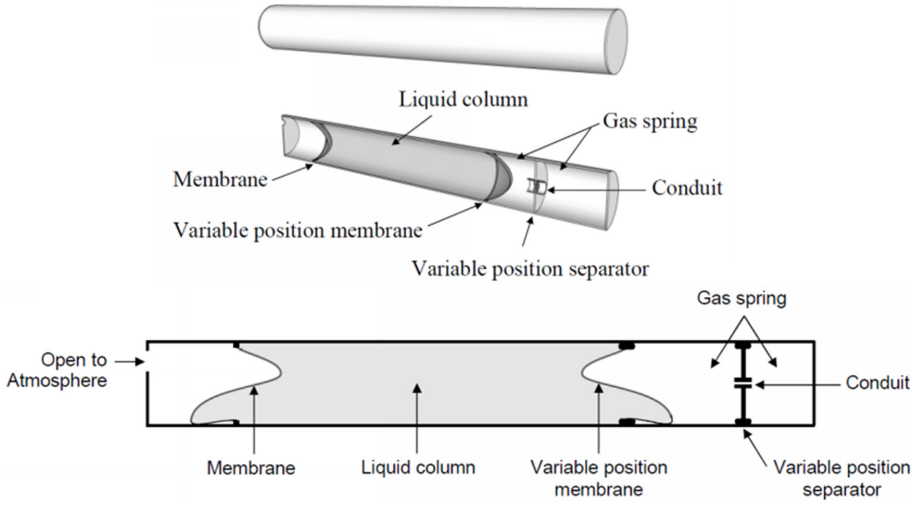


Figure 7. Hummingbird damper system.



Figure 8. Full-size Hummingbird test rig.

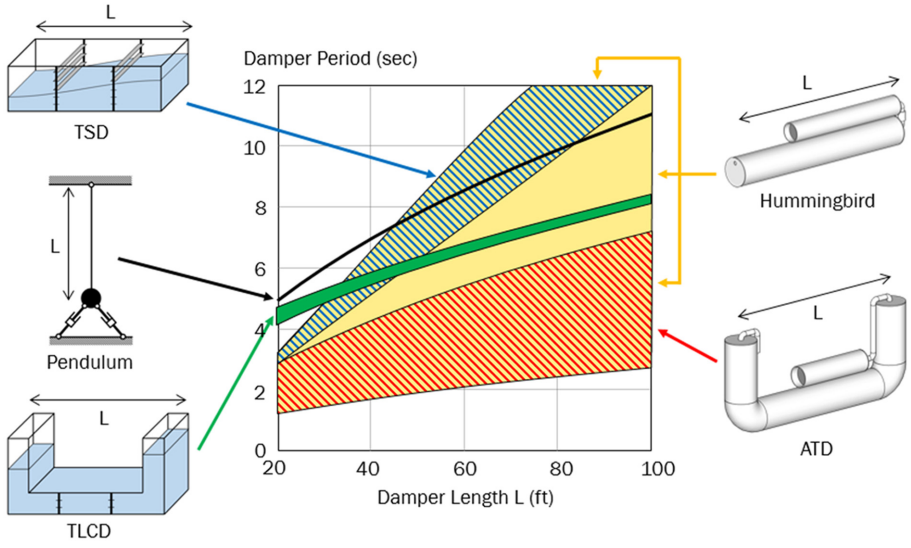


Figure 9. Typical tunable range of damper systems.

in a separate pipe to maximize the length of the water column, and this option was used for the full-size Hummingbird test rig shown in Figure 8. The test rig is being used to optimize and fatigue-test various components of the system, such as the membranes.

By eliminating the U-shaped tank and associated gravity-based stiffness, the Hummingbird damper can be tuned to an even wider range of frequencies than the ATD. The typical tunable range of different TMD systems are compared in Figure 9.

6. Conclusions

The innovative air-tuned damper system installed at 461 Dean Street has been operating successfully since 2017, and demonstrates the feasibility of cheaper, modular alternative to traditional tuned-mass dampers. As a second iteration on the air-tuned damper concept, the Hummingbird damper provides additional maintenance and space-saving benefits that facilitates damper integration into different building geometries. The Hummingbird is still water-based and therefore may not always be practical for supertall building that require the heaviest TMDs. However, it is an efficient and cost-effective option for smaller high-rise buildings, building with unusual shape and dynamic behavior, and buildings requiring a moderate amount of supplemental damping.