A mm-Scale Aeroelastic Oscillation-Based Anemometer

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A mm-Scale Aeroelastic Oscillation-Based Anemometer

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ABSTRACT
By combining the aeroelastic and vortex-forced flutter modes of a thin plastic strip, its oscillation frequency can be confined to scale monotonically with fluid velocity. This principle has been used to produce a low-cost, mm-scale anemometer that measures air speed to ±(5% + 0.5 m/s) from 1-18 m/s. The device uses a 2 mm slot-type photointerrupt detector to monitor the fundamental frequency of a 7 µm thick Kapton strip suspended parallel to air flow. This paper describes the prototype and three of the experiments that informed its design. These investigated the effect of a bluff body on flutter onset velocity, the effect of filament geometry on bending position, and the effect of the superposition of the vortex-forced and aeroelastic flutter modes on discretely-measured flutter frequency. The experiments demonstrate that a trapezoidal filament in the wake of a similarly-sized bluff body is well-suited for this novel flow measurement strategy.

INTRODUCTION
A streamer suspended in a moving fluid often flutters at a frequency that increases with the velocity of the fluid. Most people are familiar with this phenomenon from watching flags; on calm days, flags wave slowly back and forth, while on windy days they flap much more quickly. This type of aeroelastic flutter is a well-studied problem in the interaction of structures and fluids. Various efforts have clarified most aspects of flutter behavior, including the origin of the flutter instability and the tendency of the oscillation frequency to increase with fluid velocity [1, 2]. But while fluttering flags are commonly used as an informal indicator of wind speed, the possibility of an anemometer based on aeroelastic flutter hasn't been evaluated. This omission is striking because fluttering filaments ('flags') have no mechanical joints, are simple to manufacture, and have the potential to indicate fluid velocity at very small scales. These factors make aeroelastic flutter a promising basis for a new class of low-cost, miniature flowmeters.

Typical anemometers rely on lift or drag forces to indicate wind speed. For rotary vane or ball-and-cup anemometers, the lift and drag coefficients $C_L$ and $C_D$, respectively, each scale with the characteristic length $L$ of the rotor or blade, $C_{DL} \sim 1/L^2$. By contrast, although lift and drag forces are also involved, the scaling factors that define the flutter of a flag involve only the aspect ratio, not the absolute size of the flag. As derived by Argentina and Mahadevan [3], the critical wind velocity $U_C$ for the flutter of a flag scales with the flag thickness $h$ and length $L$ as $U_C \sim (h/L)^{1/2}$. As a result, an anemometer based on flutter phenomena could conceivably work at smaller scales than traditional systems based on lift or drag forces.

In this work the aeroelastic oscillation-based flowmeter consists of a small filament suspended parallel to fluid flow. As the filament flutters, its fundamental frequency is measured and compared to a frequency-fluid velocity correlation developed for the filament. The result is a small, low cost anemometer with reasonable accuracy; a system based on a 5 mm filament reliably measures air flow to ±(5% + 0.5 m/s) from 1-18 m/s, and costs less than $5. The small size and low cost could make a similar system useful in various applications unsuitable for traditional anemometers.

Though simple in principle, an aeroelastic oscillation-based flowmeter requires a filament with both a low and consistent flutter onset velocity and a monotonic flutter frequency—air velocity correlation. Practically, these challenges require a design that is both inherently unstable and inclined to oscillate in one dominant mode over a range of fluid velocities. This paper describes three experiments that informed the anemometer design. These measured the effect of a bluff body on flutter onset velocity, the effect of filament geometry on flutter measurability, and the effect of the superposition of the
vortex-forced and aeroelastic flutter modes on discretely-measured flutter frequency. The paper also describes the working prototype, and discusses possibilities for future improvement.

Figure 1: A rectangular flag of length \( L \) and height \( H \) immersed in a fluid of velocity \( U \). This is the commonly-analyzed ‘flag problem’ and is also the configuration of the experiments in this work.

Why Flags Flap

The wealth of literature on ‘the flag problem’, as it is known, is a good starting point for designing a flowmeter based on aeroelastic flutter. The problem has been addressed in contexts as varied as fish locomotion, energy harvesting, vehicle aerodynamics, and the mechanics of snoring \([4, 5, 6, 7]\). While different models have been proposed, the flag’s equation of motion is generally formulated as a balance between the stabilizing bending stiffness of the flag and a destabilizing transverse fluid loading, in addition to the flag’s inertia and drag forces. The consensus conclusion is that the flutter of a flag results from a resonant bending instability above a critical wind speed \( U_C \), which can be estimated by solving a homogenous eigenvalue problem \([3, 8]\). The configuration of the flag problem is shown schematically in Figure 1.

Argentina and Mahadevan’s linearized treatment of a flag as a 2-d airfoil is a good example of both the utility and limitations in applying the theory behind the flag problem to a real system. Their model reflects the dependencies governing \( U_C \) and the observed variation in the flutter mode with the mass ratio \( \rho_fL/m \), where \( L \) is the flag length, \( m \) its mass per unit surface area, and \( \rho_f \) the fluid density. In particular, they accurately predict that \( U_C \) decreases with increasing aspect ratio \( A' = L/H \) for flag height \( H \), decreasing thickness \( h \), and Young’s Modulus \( E \). However, their model consistently underestimates the \( U_C \) of real flags, and fails to predict the subcritical bifurcation that can lead to hysteresis in the transition to flutter. While others have examined the 3-d problem and achieved better agreement with experiments \([9]\), and numerical solutions of Navier-Stokes can simulate the flapping instability for rectangular flags \([10]\), the state of the art is better suited to qualitative than quantitative predictions of flag behavior.

Despite these limitations, previous work on the flag problem informs the basic design of an aeroelasticity-based anemometer in a number of ways. In order to maximize its functional range, the anemometer filament’s \( U_C \) must be as low as possible. The hysteresis in the transition to flutter, which could confuse automatic measurement, must also be minimized. Both of these ends can be accomplished by increasing the filament’s aspect ratio \( A' \), or for a non-rectangular filament, by increasing the front to back height ratio \( H_1/H_2\)\([11]\). \( U_C \) can also be reduced by decreasing the flag’s bending moment \( D = Eh^3/12(1-v^2) \), where \( v \) is the Poisson ratio of the flag material \([1, 9]\). Practically, this is done by using a thinner or more flexible (lower \( E \)) material.

Prior work indicates that the fundamental flutter frequency scales monotonically with fluid velocity \([1]\). An automated anemometer, however, may not be able to discern the fundamental frequency from higher modes. Pertinently, prior work by Eloy et al. \([9]\) shows that the oscillation can be biased towards a lower mode by decreasing the mass ratio \( M' = \rho_fL/m \), and Mahadevan and Argentina \([3]\) show the same bias with increased \( A' \).

EXPERIMENTS

A variety of experiments were performed to find the optimal filament size, shape and material for use in a small oscillation-based anemometer. This section reports on three of these experiments, which measured the effect of a bluff body on flutter onset velocity, the effect of filament geometry on flutter measurability, and the effect of the superposition of the vortex-forced and aeroelastic flutter modes on discretely-measured flutter frequency. All measurements were made in a 30cmx30cm wind tunnel at sea level, with the air velocity referenced against a pitot tube with a precision of \( \pm 0.1 \) m/s. The flags in the experiments were made of nylon plastic with thickness \( h = 40 \) \( \mu m \) and bending moment \( D = 9*10^5 \) Nm. Flags were mounted on thin carbon strands, and their flutter frequencies were measured discretely by a photointerrupt laser beam perpendicular to the flutter motion on the flag centerline.

Reducing Onset Velocity with a Bluff Body

One major challenge in designing an anemometer based on aeroelastic flutter is to keep the onset velocity \( U_C \) as low and consistent as possible in order to maximize the measurement range and accuracy. In order to provide consistent measurements, the hysteresis between \( U_C \) and \( U_0 \), the critical velocity at which flutter stops, should also be minimized.

Since an aeroelastic flutter-based anemometer as conceived here requires a protective housing and upstream attachment support, it is almost inevitable that the flutter of the anemometer filament will be affected by turbulence from neighboring objects. However, as pointed out by Manela et al. \([8]\), the vortex street shed by a flagpole can add a forcing term to a flag’s equation of motion, likely decreasing \( U_C \). A useful design feature in an anemometer based on aeroelastic flutter, then, might be a bluff body that perturbs the upstream flow enough to cause the transition to flutter at a lower and more consistent fluid velocity.
the bluff body can substantially decrease in terms of the reduced velocity bluff bodies upstream. Results of this test are given in Figure 3a for a variety of flag geometries. This trend holds very near the usual downwards transition velocity for the usual critical velocity after a transient disturbance on a variety of trapezoidal flags, in order to test the effect of a bluff body on flutter onset. The first velocity at which the beam as close as possible to the fixed point in order to fabricate a low-cost anemometer based on aerelastic flutter, though, a cheaper way of measuring flutter is required. For a variety of reasons including size, durability, and cost, a slot-type photointerrupt sensor is a strong choice. Since commercially-available photointerrupt sensors have a fixed laser beam width of 0.5-1mm, however, the choice necessitates a flutter amplitude at least this large. Moreover, because the photointerrupt is a discrete measurement, it is important to position the beam as close as possible to the fixed point in order to measure the fundamental flutter mode. A filament that flexes with high amplitude near the attachment point is therefore preferable.

A trapezoidal filament with a flexural rigidity $Dh$ that decreases with decreasing coordinate $x$ away from the flag attachment due to decreasing height $H(x)$. As a result, it has the potential to flex with higher amplitude near the attachment point. For this reason, a second series of experiments investigated the effect of the trapezoidal geometry on the measurability of the fundamental oscillation mode.

Two experiments were performed to better understand the effect of a bluff body on flutter onset. The first measured the onset velocities $U_D$ of a flag in the presence of different-sized bluff bodies upstream. Results of this test are given in Figure 3a in terms of the reduced velocity $U^* = LU(m/D)^{1/2}$. It is clear that the bluff body can substantially decrease $U_D$, with a larger effect as $d$ approaches $L$. The effect of a bluff body also seems weaker for flags with naturally low $U_D$ as a result of high $A^*$. Another important aspect of controlling the flutter onset velocity is reducing the transition hysteresis $U_c-U_D$. As speculated by Zhang et al. [12] and likely many others, the hysteresis may be explainable in terms of a potential barrier between a filament’s stable and fluttering states. This phenomenological description is corroborated by Pang et al. [11], who observed that $U_c$ is highly dependent on noise in the oncoming flow, while $U_D$ can be measured consistently regardless of the flow state. This behavior is perhaps not unlike Reynolds’ original observation of more variable Re at the upwards than downwards transition to turbulence in incompressible pipe flow [13].

A second experiment tested the effects of a transient disturbance on a variety of trapezoidal flags, in order to test qualitatively whether the hysteresis could be eliminated with a bluff body independent of the reduction in $U_c$. The air velocity was raised in small increments. Meanwhile, a large $(d >10 L)$ bluff body was held upstream and periodically removed. The first velocity at which the filament continued to flutter after the body was removed was recorded and compared to $U_c$ and $U_D$. As shown in Figure 3, the temporary disturbance was enough to set the flags into steady oscillation at velocities down to $U_D$. This experiment supports the potential barrier explanation as an accurate phenomenological description of the onset velocity hysteresis. This explanation indicates that both the stable and bi-stable states are allowed in the region $U_D<U<U_c$, but that the energy to move from the still state to the fluttering state must be provided by the incoming flow.

**Bending Position**

In most published investigations of flutter phenomena, the measurement instrument of choice is a high-speed camera. In order to fabricate a low-cost anemometer based on aerelastic flutter, though, a cheaper way of measuring flutter is required. For a variety of reasons including size, durability, and cost, a slot-type photointerrupt sensor is a strong choice. Since commercially-available photointerrupt sensors have a fixed laser beam width of 0.5-1mm, however, the choice necessitates a flutter amplitude at least this large. Moreover, because the photointerrupt is a discrete measurement, it is important to position the beam as close as possible to the fixed point in order to measure the fundamental flutter mode. A filament that flexes with high amplitude near the attachment point is therefore preferable.

A trapezoidal filament with $H_1/H_2 << 1$ has an effective flexural rigidity $Dh$ that decreases with decreasing coordinate $x$ away from the flag attachment due to decreasing height $H(x)$. As a result, it has the potential to flex with higher amplitude near the attachment point. For this reason, a second series of experiments investigated the effect of the trapezoidal geometry on the measurability of the fundamental oscillation mode.
Figure 4. Configuration of a trapezoidal filament with heights $H_1$ and $H_2$ monitored with a photointerrupt laser at point $x$.

Pang et al. [11] conducted measurements of trapezoidal filaments, such as the one shown in Figure 4. In addition to their finding (confirmed by the measurements of Figure 3b) that a low ratio $H_1/H_2$ reduces $U_D$, Pang et al. noted that low $H_1/H_2$ also leads to a movement of the primary filament flexure point towards the flagpole, as shown in Figure 5, below.

Figure 5. Flutter shape of trapezoidal flags based on measurements by [11]. The left image is of an elongated trapezoidal filament of $H_1/H_2 \ll 1$, the right is a filament with $H_1/H_2 \gg 1$. Lines are drawn on the photographs to emphasize the median positions based on the deflection at $x = L$.

Figure 6 shows that the shift to forward deflection at the median position can be predicted via classical plate theory, $\nabla^2 \nabla^2 y(x) = P/D$ for applied pressure $P$. The instantaneous small deflection $y(x)$ is similar to that of a variable-width cantilever plate under uniform pressure.

$$y(x) = \frac{PH_2x^3}{120L D H(x)} (120L^3 - 10L^2x + x^3)$$

(1)

Based on this approximation, the flag size, beam width, and maximum flutter amplitude, it was possible to predict the possible measurement locations for flags of different shapes. These predictions are compared to experiment for two different ratios $H_1/H_2$ in Figure 7. While the actual flutter detectability increased smoothly towards the rear of both flags, in contrast to the discrete behavior of the plane-bending approximation, the overall trend of enhanced detectability at the front end with lower $H_1/H_2$ was followed.

Figure 6. A model for the deflection of a tapered plate of length $L$ under uniform pressure loading in terms of various front to back height ratios $H_1/H_2$ shows similarity to the median positions of the flutter waveforms highlighted in Figure 5.

Figure 7. Tests for flutter measurability of different-shape filaments with a photointerrupt detector at different positions $x$ along the filament. Measurements are normalized to the highest frequency measured for the filaments. The predictions are based on the 0.5mm beam width, the observed maximum flutter amplitude, and the plane bending approximation from Figure 6. Inset: Example of the apparatus for these tests with an $H_1/H_2 = 1$ flag.
Hybridization with Vortex-Forced Flutter

In addition to the effect on flutter onset, the bluff body can have an effect on flutter frequency. In fact, as shown by Wang et al. [14], the forcing from an upstream disturbance can help make the flapping more regular. Wang shows that in one case, a 1-d filament in a vortex street oscillates at the von-Karman vortex shedding frequency, which increases predictably with velocity within certain Re ranges [15]. While a purely vortex-forced flag motion requires too large of a bluff body for a miniature flowmeter, the effect of a bluff body may still be useful to ‘smooth’ an otherwise irregular air velocity – flutter frequency correlation. A third set of experiments was conducted to investigate this effect.

A rectangular nylon flag of $L = 8\text{mm}$ and $A^* = 4$ was placed in the wakes of different-sized cylindrical bluff bodies of diameter $d$. As shown in the inset of Figure 8, the filament was placed a distance $d$ to the side and $d$ downstream the cylinders, to avoid reduced local velocity over the flag. The flutter frequency—air velocity correlation of the flag was then measured with a discrete photointerrupt at $x = 3L/4$, and reported as either Strouhal number $St = fL/U$ or dimensionless frequency $F^* = fL/U$.

![Figure 8. Flutter of a flag in the wake of different-sized cylindrical bluff bodies. The dashed trace shows the behavior of the same flag in free stream. Clearly, larger vortex structures do more to smooth the flutter and lower $U_C$ than those from smaller bluff bodies. Inset: Placement of the filament in this experiment. Considering only the 2d interactions, the flag should only be expected to oscillate under the influence of one side of the vortex street.](image)

For the purposes of an oscillation-based anemometer, the most applicable results are summarized by the representation of the data in Figure 8. Larger bluff bodies do more to influence the flutter behavior, with a monotonic correlation and significantly lower $U_C$ by $d=2L$.

Figure 9 shows the ratio of $St_{flag}/St_{cylinder}$ for the same experimental run. Clearly, the oscillation stayed well below the vortex frequency, in contrast to the conclusions of Wang et al. It is possible that the 2-D flag immediately behind the bluff body impeded vortex formation in these experiments in a way that the effectively 1-D filament’s used in their experiments did not. However, the more likely explanation is that behavior of a flag in a vortex street is more complicated than previously described, and likely depends on the flag’s stiffness $D$, the vortex strength, phase relation, and other factors.

![Figure 9. The ratio of the flag flutter Strouhal number $St_{flag} = fL/U$ to the vortex shedding frequency $St_{cylinder} = 0.198(19.77/Re_d)$. In the experiment, the flag flutters at a frequency well below the frequency of vortex shedding.](image)

PROTOTYPE

A prototype aeroelastic anemometer was designed based on the experiments described above, in addition to separate investigations of the effect of filament shape, material, attachment strategy, measurement strategy, and system integration in a flow-accelerating nozzle. The resulting system is shown schematically in Figure 10 and to scale in Figure 11. It consists of a trapezoidal Kapton filament with $L = 5\text{mm}$, $h = 7\mu\text{m}$, $H_1/H_2 = 0.1$ and $A^* = 10$ in a carbon fiber housing. The housing is integrated with a rectangular bluff body of $d = L/3$ which reduces both critical velocities to ~1.1 m/s. The filament is attached to a carbon strand at the nozzle throat and allowed to swing in the path of a 2mm photointerrupt sensor with a beam intersecting the filament at $x = L/2$. The filament plane is aligned with the axis of the bluff body and carbon strand, both of which are oriented at an angle of 10° to the photointerrupt beam. The offset aids detection of the flag by presenting more filament material to occlude the photointerrupt beam.

![Figure 10. Schematic of the aeroelastic oscillation-based anemometer. Air flows from points 1 to 4. A bluff body perturbs the flow at point 2.](image)
As shown in Figure 12, the prototype performs best in the range 1-18 m/s, with an accuracy of approximately ±(5% + 0.5 m/s). However, the system has a slow response time approaching 15 seconds per tested velocity. This lag is attributable to two factors. One is a programmed delay that causes the system to wait until the frequency reaches a repeating value. A second factor is an inherent latency in the frequency measurement strategy; in order to provide a more consistent measurement, the system records the period between successive filament passes, and then applies a median filter to the resulting array of periods to select the output value.

Several simple modifications could likely improve the prototype’s performance. A more compact housing, as shown in Figure 13, could likely protect the filament without adversely affecting the measurement, and might allow more air to pass through the nozzle. Another potential improvement might be the incorporation of an adaptive digital signal processing strategy. An algorithm calibrated to the response of a particular filament could conceivably give an accurate measurement even without a monotonic flutter frequency–velocity correlation, by comparing the signal strength in different vibration modes to reference values.

CONCLUSION

The flutter frequency of a thin plastic strip suspended parallel to fluid flow can provide a good indication of fluid velocity. A main advantage of this approach over traditional mechanical anemometry is scalability; because the onset of flutter is theoretically independent of the filament’s characteristic length, a flowmeter based on this principle could be manufactured at small scales. This effort focused on a mm-scale implementation of the aeroelastic oscillation-based anemometer, and presented three experiments that guided prototype design.

It was found that a trapezoidal-shaped filament with a large aspect ratio enabled discrete measurement of the first flutter mode at a position in the middle of the flag. A bluff-body upstream of the flag also helped to lower both critical velocities $U_C$ and $U_D$, and to make the flutter frequency–velocity correlation more monotonic as measured with a discrete photointerrupt. Ultimately, the flutter frequency of a 5mm filament mounted in a 1.5cm flow-accelerating tube measured air flow to ±0.5 m/s from 1-18 m/s and ±3 m/s to 25 m/s. Because the components for this prototype cost less than $5 including electronics, a next-generation oscillation-based anemometer could be a useful tool for a variety of flow measurement applications.

Productive future work on the aeroelasticity-based flow measurement concept may involve the design of a more robust and better streamlined filament housing, tests on alternative flow geometries (such as flow normal to the long axis of the filament).
filament), or the development of an adaptive Digital Fourier Transform -based signal processing strategy. The latter could potentially allow accurate flow measurement even with a less-optimized filament geometry. Further analysis of the scaling relations could also clarify the prospects for a MEMs-scale flowmeter based on aeroelastic flutter.

Additionally, an observation made in the course of this research could be of interest to the theoretical ‘flag problem’ in general. The data supports the theory that the hysteresis in the transition to and from the flutter state is explainable in terms of an activation energy that is usually provided by vorticity in the upstream flow.

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