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On the use of PVDF for morphing wing pressure indicators

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The goal of this article is to investigating the possibility to capture the physical effect on the flow via a hybrid piezoelectric-shape memory alloy actuation at high Reynolds numbers using Polyvinylidene Fluoride (PVDF) based pressure indicators at the trailing-edge of morphing wing prototype. The aim is to identify both the high- and low-frequent turbulent structures using distributed pressure indicators and thereby identify the actuation effect on the flow. To this end the design of the PVDF based pressure indicator as a function of the Reynolds number, desired frequency and maximum attenuation will be described. Following this description of the design the numerical results are presented. Finally the experimental results will presented and compared to the turbulent structures identified using tomographic Particle Image Velocimetry. It will be shown that the proposed PVDF based pressure indicator is capable of capturing the aerodynamic phenomena on the trailing edge of an airfoil at high Reynolds numbers.

electro-active morphing, PVDF, piezoelectric sensors, turbulence

1 Introduction

Conventional fixed wing airfoil geometries are usually the result of a design compromise optimizing the shape only for some parts of the mission profile. Control surfaces while modifying the aerodynamic profile of the wing and thereby extending the mission profile are usually characterized by poor aerodynamic performance and efficiency [17]. Adaptive or morphing structures hold the potential to solve this problem and studies on wing deformation are subject of much interest in the aerospace domain. Recent advances made in the field of smart-materials have renewed this interest [18, 9].

The Electro-active morphing for micro-air-vehicles (EMMAV) research program, which was created as part of the French foundation of «Sciences et Technologies pour l'Aéronautique et l'Espace»'s effort to develop micro- and nano-air-vehicles and is composed of three French laboratories (IMFT, LAPLACE, ISAE), aims at optimizing the performance of micro-air-vehicles in realistic environments via electro-active morphing [12]. During the course of this project a prototype wing was developed with embedded Shape memory alloys (SMAs) and trailing-edge piezoelectric actuators enabling both large deformations ($\approx 10\%$ of the chord) at limited frequency ($\leq 1 Hz$) and small deformations (several μm) at high frequencies ($\leq 100 Hz$) [3]. Figure 1a shows the developped prototype. The characteristics of the SMA technology, which were activated using the well understood Joule effect [8], make it especially suitable to optimize the shape of the wing and to control the flight [2, 15]. The high-frequent but low amplitude piezoelectric technology on the other hand is useful to produce trailing-edge vortex breakdown [11, 6, 16].

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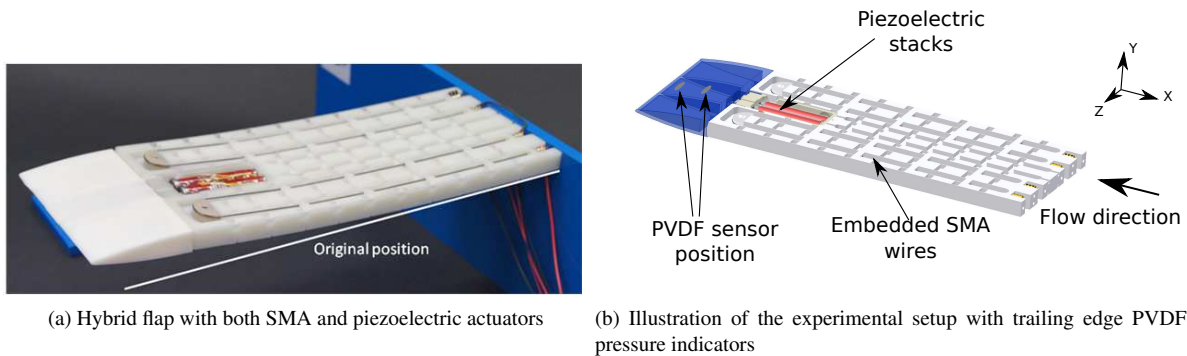


FIGURE 1

While the influence on the flow of both the SMA and piezoelectric part of the hybrid actuation mechanism has been proven [5, 13] a real-time control has yet to be realized. One of the issues which will be addressed in this article is the design of a sensor capable of identifying the turbulent structures for the high-frequent piezoelectric actuation mechanism. Conventional visualization and indication techniques such as Particle image velocimetry (PIV) measurements and off-the-shelf pressure sensors are both costly and/or associated with a significant integration effort. PVDF based pressure indicators provide a way to leverage the integration effort. Previous works have already demonstrated the use of PVDF as pressure sensors. Shirinov developed an encapsulated differential PVDF pressure sensor where the signal is generated by the pressure difference induced flexion [14]. Nitsche used PVDF in order to determine the transition from laminar to turbulent flow [10]. Lee designed a matrix of PVDF sensors in order to measure the pressure [7]. Whereas Lee reconstructed the non-stationary pressure signal by determining the transfer function between the pressure and the measured signal, Shirinov used a charge amplifier and an integrator in order to reconstruct the pressure signal from the measured signal.

This work is developed as follows : in a first part we will recall the fundamental properties of PVDF. Then we describe the sensor design. Subsequently we give an outlook for the final article and draw some preliminary conclusions.

2 PVDF

Polyvinylidene Fluoride (PVDF) is a semi-crystalline polymer exhibiting piezoelectric properties. As such the material is governed by the fundamental piezoelectric equations given in equations 1 and 2 :

$$\{S\} = [s^E] \cdot \{T\} + [d] \cdot \{E\} \quad (1)$$

$$\{D\} = [d] \cdot \{T\} + [\epsilon^T] \cdot \{E\} \quad (2)$$

where $\{S\}$ is the strain vector, $[s^E]$ is the compliance matrix, $\{T\}$ is the stress vector, $[d]$ is the matrix of piezoelectric constants, $\{D\}$ is the dielectric displacement vector, $[\epsilon^T]$ is the permittivity matrix and $\{E\}$ is the electric field vector. Compared to other piezoelectric materials such as Lead zirconate titanate (PZT) PVDF has a significantly lower and opposite charge constants. Yet, the polymeric nature of the material makes it an interesting candidate material for sensors [1].

3 Sensor Design

Apart from the reconstruction of the pressure signal one of the most important issues in the development of the PVDF based pressure indicator is the dimensioning of the sensor in order to provide sufficient sensitivity in the frequency range of the aerodynamic phenomena. Additionally the sensor should be resilient to interferences. Evidently the ideal sensor would be infinitely small in order to provide the best accuracy and lowest amount of interference but since this sensor would generate a nearly undetectable signal a compromise has to be found in between the attenuation in function of the frequency and sensor dimension given in Figure 2b and the recoverable signal.

Using Figure 2b as a mean to estimate the attenuation we get :

$$\frac{\phi_m}{\phi} = f \left(\frac{\omega r}{U_c} \right) \quad (3)$$

where ϕ_m is the measured spectral density of the sensor, ϕ is the real spectral density of the signal, r is the radius of the sensor and U_c is the convection speed.

The classical definition of the convection speed is :

$$U_c = 0.6U_\infty \quad (4)$$

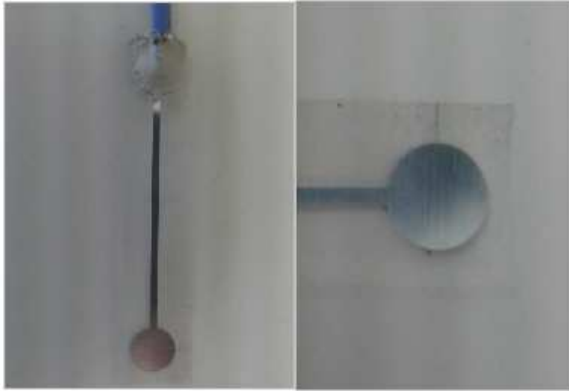
where the freestream velocity U_∞ can be replaced by the desired Reynolds number knowing that the Reynolds number is defined as :

$$Re = \frac{U_\infty c}{\nu} \quad (5)$$

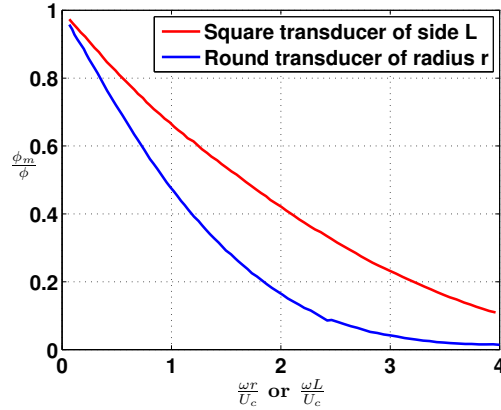
where c is the chord of the wing and ν is the kinematic viscosity. Now we can rewrite equation 3 using equations 4 and 5 and we get :

$$r_{max} = \left[0.6 \frac{\nu}{c} f^{-1} \left(\frac{\phi_m}{\phi} = 0.5 \right) \right] \frac{Re_{min}}{\omega_{max}} \quad (6)$$

Equation 6 provides us with a method to determine the maximum allowable sensor dimensions in function of the maximum tolerable attenuation and the Reynolds number.



(a) Designed PVDF pressure indicator



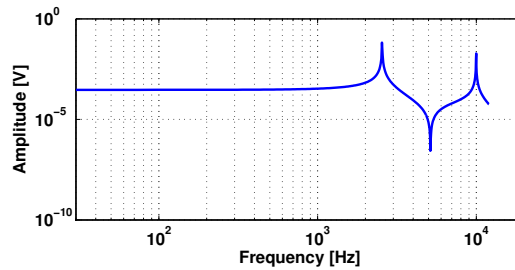
(b) Attenuation of the frequency spectral density in function the normalized frequency [4]

FIGURE 2

4 Outlook and Conclusion

Parameter	Value
Re	200.000
ω	1000 Hz
c	0.5 m
$\frac{\phi_m}{\phi}$	50%

(a) Sensor parameters



(b) Frequency response of the sensor

FIGURE 3

Based on the investigations by Corcos we defined a new method to estimate the allowable size of a PVDF based pressure indicator. This allows us to dimension the PVDF sensors according to the parameters of the flow and the structure which are given in Table 3a. Using these values a maximum radius of $r_{max} = 3 \text{ mm}$ for the PVDF pressure indicator was determined. Using ANSYS the frequency response of the sensor was determined. This frequency response, shown in Figure 3b, clearly illustrates, that the first mode of the structure is well above the bandwidth being considered in the experiments. One of the fabricated pressure indicators is shown in Figure 2a. The sensors are currently being tested on the hybrid prototype as is shown in Figure 1b and the values are being correlated to the velocity signals obtained using PIV. This way a comparison of the turbulent structures identified using both PIV and PVDF sensor measurements can be conducted.

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