On the use of PVDF for morphing wing pressure indicators

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SUMMARY – The goal of this article is to investigate 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 be presented and compared to the turbulent structures identified using high-speed 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.

Keywords – 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 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 1 shows the developed 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].

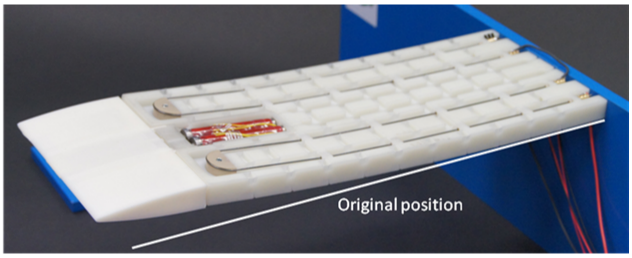

Fig. 1. Hybrid flap with both SMA and piezoelectric actuators

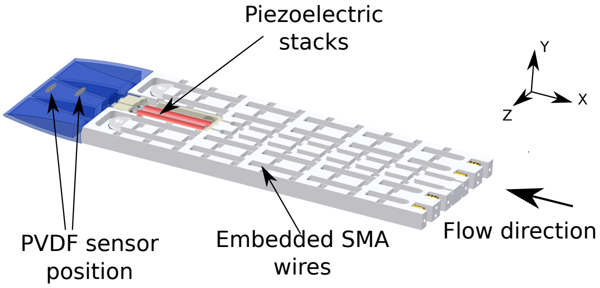

Fig. 2. Illustration of the experimental setup with trailing edge PVDF pressure indicators

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. Conven-

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tional visualization and indication techniques such as Particle image velocimetry (PIV) measurements and off-the-shelf pressure sensors are bost 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 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 the experimental results will be presented and the encountered issues addressed. Finally an outlook is going to be provided and strategies for improving the results will be discussed.

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 :

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

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

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 4 and the recoverable signal.

Using Figure 4 as a mean to estimate the attenuation we get :

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

were 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 :

$$U_c = 0.6 U_\infty \tag{4}$$

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

$$Re = \frac{U_\infty c}{v} \tag{5}$$

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

$$r_{max} = \left[0.6 \frac{v}{c} f^{-1}\left(\frac{\varphi_m}{\varphi} = 0.5\right)\right] \frac{Re_{min}}{\omega_{max}} \tag{6}$$

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.

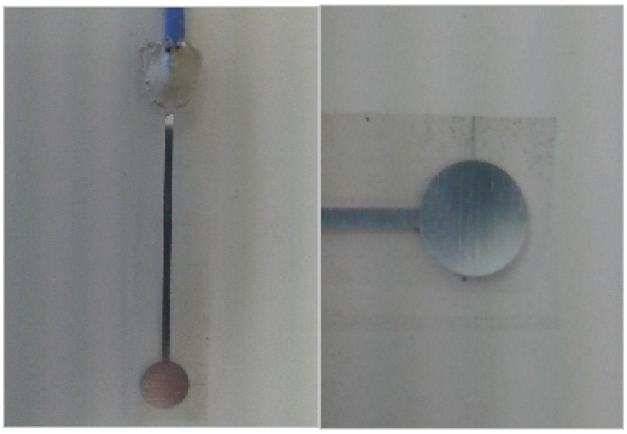


Fig. 3. Designed PVDF pressure indicator

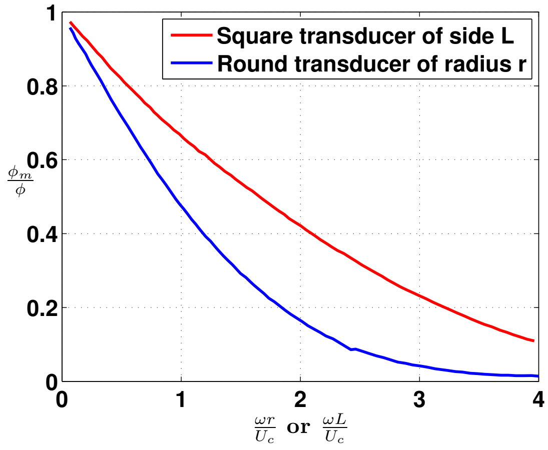


Fig. 4. Attenuation of the frequency spectral density in function the normalized frequency [4]

The experimental parameters for the hybrid morphing wing, which are given in Table 1, provided us with a mean to define the geometry of the PVDF based pressure indicator. These values defined a maximum radius of $r_{max} = 3\,mm$ for the PVDF pressure indicator. The commercial Finite Element (FEM) software ANSYS was used to plot the frequency response of the sensor shown in Figure 5. This frequency response clearly indicates the presence of the first mode to be well above the desired investigation frequency ω.

Tableau 1. Sensor parameters

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

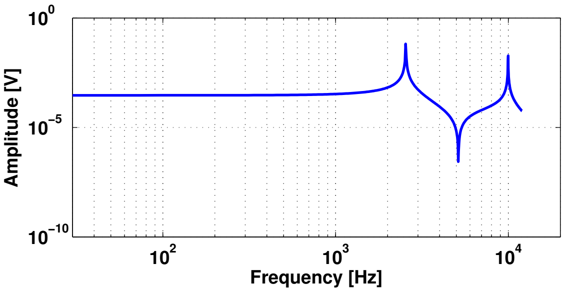


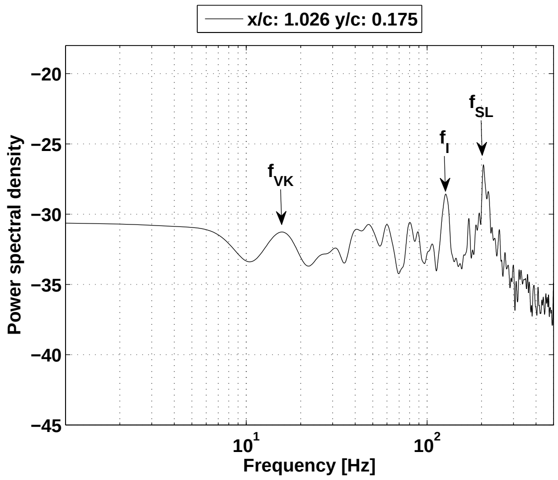
Fig. 5. Frequency response of the sensor

4. EXPERIMENTAL RESULTS

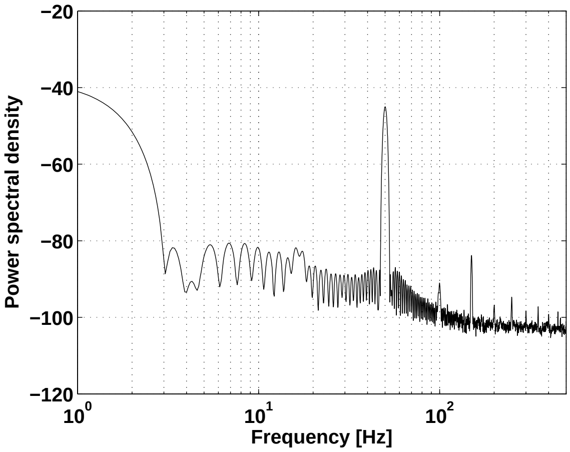
In order to test the functionality of the PVDF based pressure indicator the hybrid morphing prototype illustrated in Figure 1 was equipped with the material. As the primary goal of the pressure indicator is to identify turbulent structures the data was compared to the Power spectral density (PSD) of the PIV measurements for the unactuated case and for the case with 30Hz of actuation. To verify the results a set of 10 measurements was conducted. The results were grouped according to the actuation frequency. For each case the corresponding PSD of the PIV is provided. Comparing the results two things are instantly noticable : first the considerable electronic noise induced by the network and secondly the influence of the actuation on the PSD. To reduce the influence of the network the data was post-processed using a high-pass filter.

4.1. 0Hz actuation frequency

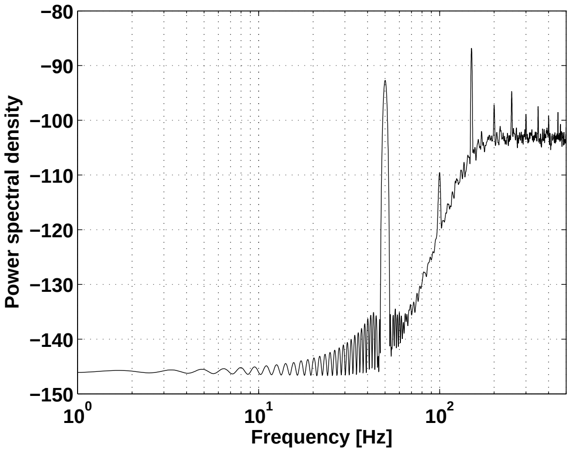
Considering the data obtained for the case without actuation, shown in Figure 6, one can see that as previously mentioned the network contributes a considerable amount of electronic noise. Hence, the primary frequency captured by the PVDF pressure indicator are the 50Hz of the network. Nevertheless the pressure indicator is still capable of capturing the frequency of the shear layer at 201Hz as can be seen by comparing the PSD obtained from the PIV measurements in Figure 6a to the PVDF PSD in Figure 6b. Applying a Butterworth filter to the measured data further highlights the shear layer frequency (see Figure 6c).



(a) Vertical velocity component V from PIV measurements



(b) Unfiltered PVDF pressure indicator

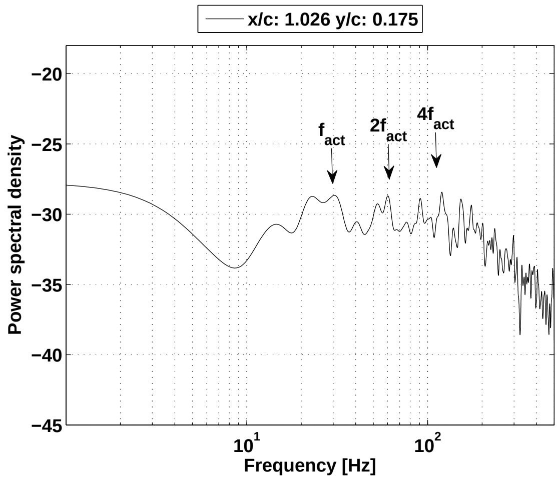


(c) Filtered PVDF pressure indicator

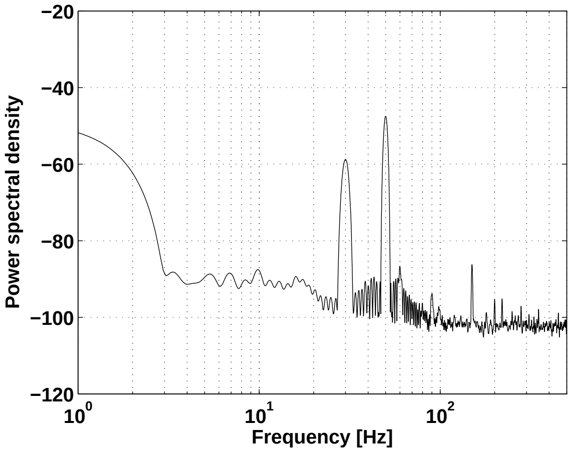
Fig. 6. PSDs without actuation

4.2. 30Hz actuation frequency

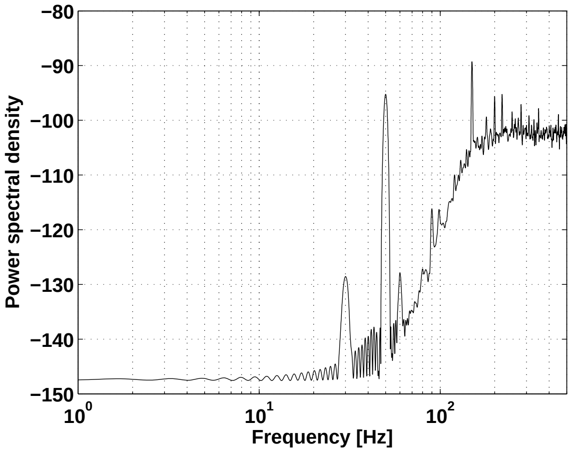
When comparing the data from the pressure indicator for the case without actuation to the case with actuation one can directly see that apart from the influence of the network the sensor also captures the actuation frequency and its subharmonics. Furthermore it can be noticed that similar to the PSD obtained from the PIV measurements, the PSD from the pvdf pressure indicator also captures the actuation induced reduction of the spectral energy especially at the shear-layer frequency. Once again the network induced a considerable amount of noise and hence the data had to be filtered using a 5th order Butterworth filter.



(a) Vertical velocity component V from PIV measurements



(b) Unfiltered PVDF pressure indicator



(c) Filtered PVDF pressure indicator

Fig. 7. PSDs with 30Hz actuation

5. CONCLUSIONS

The present article describes the design and development of a PVDF based pressure indicator based on the requirements imposed by the need for sufficient sensitivity in the frequency range of the aerodynamic phenomena under study. The design parameters were highlighted, the corresponding frequency response was shown and the sensor results were compared to the PIV measurements in the windtunnel.

One of the main issues identified was the strong presence of electronic noise and the subsequent need for filtering. Whereas the actuation frequencies were also captured by the PIV measurements their strong presence in the data obtained from the PVDF sensor posed a second issue.

Nevertheless the data indicates that while a non-negligible amount of noise is present in the measurements, the pressure indicator is still capable of capturing the frequency of the shear layer. This positive result, while still at an early stage, might help to develop an integrated sensor-actuator system with an optimum actuation aimed at reducing drag and aerodynamic noise.

To tackle the issue of electronic noise a more integrated system is being considered in order to reduce the distance between pressure indicator and charge amplifier. Furthermore, the positioning of the sensor also has to be investigated to guarantee a high signal quality.

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