Dynamic Calibration of Low-Cost Gas Sensors for Dispersion Experiments

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1 INTRODUCTION

Simulating pollutant dispersion in a wind tunnel is normally achieved using passive tracer gases. Currently, the only available technology for measuring gas concentration with sufficient bandwidth for time-domain correlations is the fast-flame ionization detector (FFID), which is able to measure hydrocarbon concentrations down to low PPM, with bandwiths up to 200 Hz. This is a complex and costly instrument with a large probing head and bulky umbilical, making it unsuitable for rake-type arrangements. In addition to its large size, the probing head generates waste heat and exhaust gas, and can therefore be very intrusive.

On the other hand, platinum-catalyst pellistor sensors for hydrocarbon concentration are a mature technology; commonly used in safety applications, they are inexpensive and readily available from a number of commercial suppliers. Although commercially available pellistors are quite small (~20 mm diameter) compared to FFID heads, they have a fairly large sampling volume and a very low bandwidth (as low as 0.02 Hz).

A technique has therefore been developed to dynamically calibrate pellistor sensors, in order to provide a much less intrusive alternative to FFID for tracer gas measurement in turbulent flows. In addition, the small size and low cost of pellistor probes would enable the deployment of spatially-resolved rakes of concentration probes, providing otherwise unavailable simultaneous spatial correlations and significantly reducing required wind tunnel run times.

2 METHODOLOGY

A commercially-available ATEX-compliant pellistor sensor having a sensitivity of ~3mV/1000 PPM, an RMS signal noise of ±8 PPM and a bandwidth of 0.06 Hz to 0.12 Hz (figure 1a) was fitted with a sealed plenum chamber (of volume ~150 mm^3) with an inlet and exhaust that allowed the sample gas to flow evenly over the 14-mm diameter sensing surface. The plenum was fed with a mixture of clean air and a 15,000 PPM propane-air tracer solution (at a total flow rate Q < 1.5 L/min), and a computer-controlled servovalve was used to control the mixture ratio. Great care was taken to balance the back pressure in the gas systems, and to ensure complete mixing upstream of the sensor. The resultant tracer concentration C could then be controlled via the servovalve to provide an arbitrary, time-varying $C(t)$ in the plenum. The sampling tube from a FFID probe (Cambustion model HFR400) was also inserted into the plenum, in order to provide a reference concentration $C_{ref.}$ in the plenum. The sampling tube had an inner diameter under 1 mm and was ~300 mm long; although it is understood that the length of the FFID sampling tube causes a signal time shift (which is typically calibrated out), the absolute timing of the concentration signals were not relevant in this case.

Analogue signals from the pellistor and reference FFID were acquired simultaneously using a typical 16-bit data acquisition system, and no analogue signal conditioning or filtering was used for the pellistor.

2.1 Dynamic calibration

A dynamic calibration of the pellistor was then carried out using a discrete spectral reconstruction technique often applied for pressure-based measurement systems [1]. The servovalve was actuated to provide the plenum with a concentration that varied nearly sinusoidally in time (figure 1b), with amplitudes adjusted as required to ensure consistent peak concentrations. The spectral energies of the signals $C(t)$ and $C_{ref}(t)$ were compared over a narrow band around the forcing frequency to obtain the gain G and phase shift ϕ at each forcing frequency f_0 (figure 2). As would be expected for a low-

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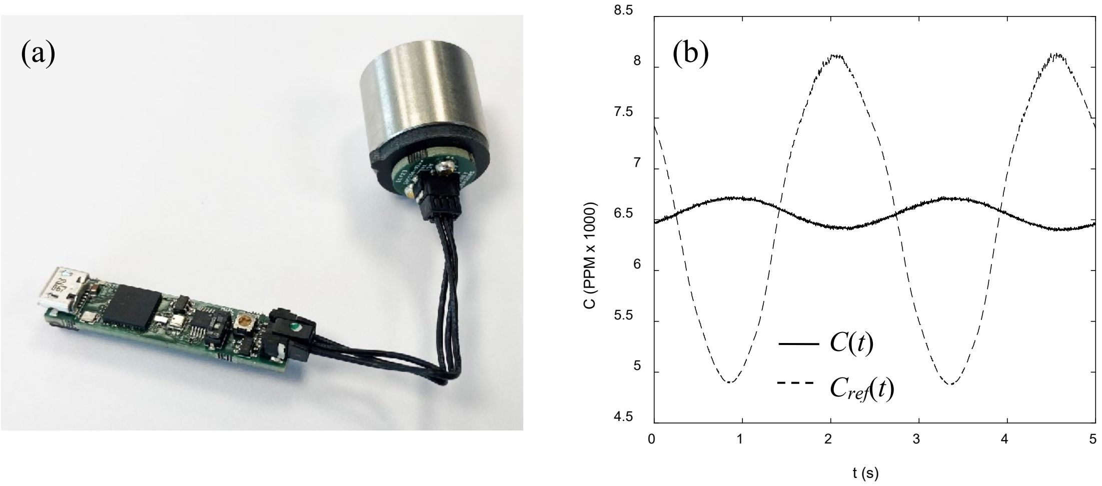

Figure 1: (a), Pellistor sensor system; (b), calibration signal.

bandwidth instrument, G decreases rapidly with increasing f_0, to a minimum of $G \sim 0.004$ at $f_0 = 2$ Hz. It should be noted that this high level of gain also resulted in the signal noise being amplified to a level equivalent to ±2000 PPM at 2 Hz. Continuous functions $G(f)$ and $\phi(f)$ were then inferred by third-order interpolation.

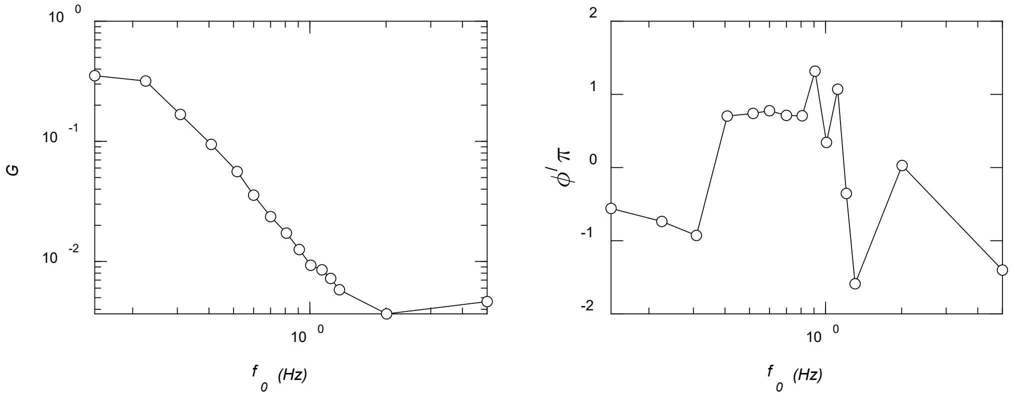

Figure 2: Dynamic calibration results. Left, gain; right, phase shift.

During measurement, the spectral decomposition of the pellistor signal was obtained by fast-Fourier transform (FFT); the amplitudes were rescaled by $G(f)$ and phases were shifted by $\phi(f)$. The signal was then low-pass filtered at 1.7 Hz, and the filtered time-domain signal was reconstructed by inverse FFT.

3 RESULTS AND DISCUSSION

To test the effectiveness of the dynamic calibration, the concentration in the plenum was varied arbitrarily in time using a test signal $C(t)$ which was designed particularly to challenge the pellistor. Figure 3 compares the resultant C_{ref} with both the raw pellistor signal and the dynamically calibrated signal. The process of dynamic calibration yielded a significant improvement in the time response of the pellistor, reducing the mean square error $\varepsilon = \mathrm{mean}(C-C_{ref})^2/C_{ref}^2$ from 0.11 to 0.0071 over the range shown. A high-frequency 'ringing' in the calibrated signal remains, as a result of the poor signal-to-noise ratio at higher frequencies.

Figure 4 compares the same dynamically calibrated signal and reference concentration in the spectral domain. Again, the two agree very well for $f < 1.5$ Hz. Over the range 1.5 Hz $< f <$ 1.66 Hz, the poor

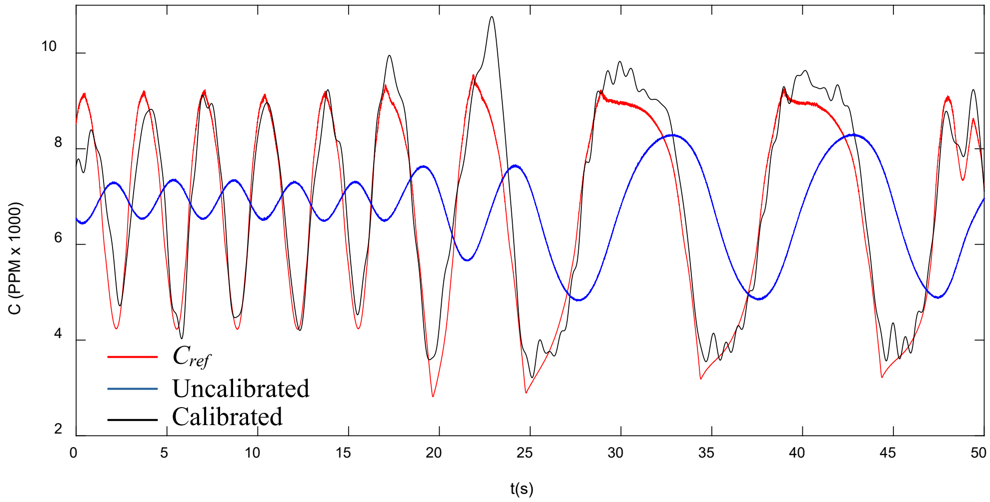

Figure 3: Response of dynamically calibrated pellistor to an arbitrary signal.

signal-to-noise ratio results in a weaker agreement, as the amplification of signal noise begins to dominate. For $f > 1.66$ Hz, the pellistor signal becomes vanishingly small as a result of the low-pass filter applied.

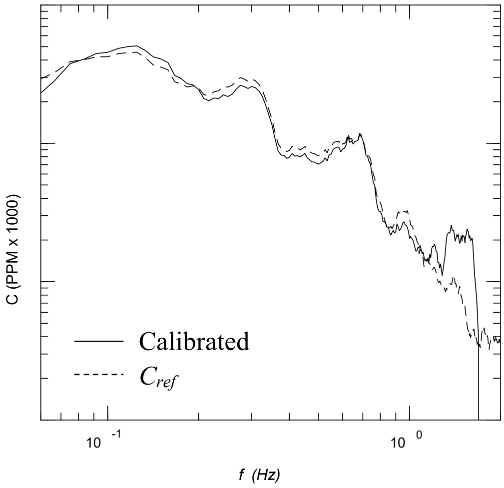

Figure 4: Spectral comparison of C and C_{ref} following dynamic calibration.

The good agreement shown here demonstrates that it is indeed possible to significantly improve the time response of low-cost pellistor sensors by applying a discrete-frequency dynamic calibration techniques developed for use with ultra-low range pressure sensors. Given that no analogue signal pre-conditioning was applied, these results demonstrate that the bandwidth of a pellistor sensor can be increased by at least a factor of 14, to 1.66 Hz.

4 CONCLUSIONS AND FUTURE WORK

Although the bandwidth remains too small for a dynamically-calibrated pellistor sensor to entirely replace FFID for time-domain tracer concentration measurements, there are some atmospheric wind-tunnel tracer concentration measurement applications in which the bandwidths of interest are very low, with frequencies of interest of order 10 Hz [2]. In stratified wind tunnels particularly the time-scales can be even lower [3]. Furthermore, because of their low cost and size, rakes of pellistor sensors are a tractable means of acquiring mean concentration field data without the extensive time required for pointwise scans, offering a powerful complementary capability to conventional FFID. On the other hand, a bandwidth of 1.6 Hz is sufficient to yield well-resolved time-domain measurements in field applications.

The results shown here were based on raw (unconditioned) signals from a pellistor sensor developed for explosion safety purposes. With appropriate analogue signal pre-conditioning (gain and filter), it is expected that the signal-to-noise ratio of the sensor can be significantly improved at higher frequencies, and the usable bandwidth increased. Furthermore, the response time of the pellistor may be dominated by the effect of the anti-explosion porous shield covering the catalyst, through which the sample gas must diffuse. It is possible that the time response may be further improved by modifying the design of the plenum.

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