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Non-linear transfer function identification of pressure probes using Siren Disks

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ABSTRACT

This article presents a Siren Disk proof of concept for the dynamic excitation of pressure probes, and a method to reconstruct distorted signals due to pneumatic channels. Constraints in sensor installation require placing a pressure transducer distant from the measurement point. The transducer is usually connected through a pneumatic channel – creating a probe, which alter its dynamic response. The Siren Disk is used for the identification of transfer functions of different pressure probe geometries. The device is capable of producing pressure signals up to 10 kHz and 3.5 bara (peak-to-peak = 2.5 bars). The transfer function is obtained through the comparison of the probe signal to a flush mounted reference transducer that is subjected to the same pressure signal. The response of the probes was shown to be highly non-linear. Hence, a multi-dimensional transfer function is developed for the system identification of the probes. The function is based on the Fourier series, and consists of a set of sub transfer functions describing the average gain and phase lag for the offset and the harmonics. The approach is well suited to capture the non-linear frequency response of complex sensor installations. Experiments show that the flat response of transducers is jeopardized by the introduction of the low pass filter behavior from the pneumatic channels. The probe's signal was significantly distorted compared to the reference signal. The inverse transfer function is used to reconstruct the probe's signal in the time domain. Good agreement is found between the reconstructed and the reference signals even at excitation frequencies beyond the probe's resonant frequency. Hence, highlighting a wide range of validity for the proposed method.

1. Introduction

Time resolved accurate pressure measurements are of pronounced importance in the control, monitoring and understanding of a wide range of mechanical and aerospace systems. If the required measured pressure is constant over time, the transducer's sensitivity is the only factor that governs the measurement accuracy. However, many applications require the accurate measurement of unsteady pressures, which is crucial to observe and understand phenomena like turbulence, flow separation onset, or periodic flows in turbomachinery. Additionally, some of these applications are constraint in space (e.g. small-scale turbomachinery), or exposed to extreme temperatures (e.g. gas turbines), which prevent the flush mounting of fast response transducers. Hence, imposing the connection of the pressure transducers distant from the point of interest via pneumatic channels – creating a probe. In that case, further parameters are required to perform accurate time-resolved pressure measurements.

Bean [1] identified six parameters for the characterization of pressure transducers used in time-resolved measurement: (1) gain, (2) phase lag, (3) resonant frequency, (4) damping ratio, (5) rise time, (6) and overshoot. The identification of these parameters requires dynamic calibrators, which are capable of generating periodic pressure signals with controlled amplitude and frequency, or aperiodic step or impulse pressure signals with a short rise time and controlled amplitude. Aperiodic calibrators are generally based on shock tube or fast opening valve concepts [1–8], whereas periodic calibrators are either variable volume generators, rotating valves or sirens [1,2,5,9–14].

1.1. State of the art

Aperiodic calibrators provide time domain calibrations where gain and phase lag are identified by the ratio of the output to the input signals' Fourier (or Laplace) transforms [2,5]. Shock tubes are widely adopted as aperiodic calibrators; however, the incomplete burst of the diaphragm is a common issue, which results in low frequency pressure disturbances after the shock, making it challenging to obtain an accurate transfer function [3]. A similar device to a shock tube is the pressure pulse generator of Aronson and Waser [15] that relies on the

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Nomenclature

A	Amplitude
$\overline{A}$	mean
A_n, B_n, Q_n	Fourier series coefficients of nth harmonic
D	diameter (mm)
f	excitation frequency (Hz)
f_{res}	1st resonant frequency (Hz)
G_n	gain in the nth harmonic
L	length (mm)
L_V	vertical length (mm)
L_H	horizontal length (mm)
n	harmonic order
n_h	total number of harmonics
q	unsteady signal
q_0	time averaged offset
t, T	time (s)
Φ_n	phase angle of nth harmonic (deg.)
ω	frequency (Hz)
FFT	fast Fourier transform
gof	goodness of fit
hpf	hole passing frequency (Hz)
Meas.	measured
Recon.	reconstructed
Ref.	reference

rapid venting of a known static pressure on the sensor to be calibrated using a fast-acting poppet valve. The system is able to build up pressures up to 68 bara in a rise time less than 100 µs. For broadband calibrations, fast opening devices are used in order to cover frequencies lower than 100 Hz in addition to shock tube tests [2,5].

Air periodic calibrators are generally used for low frequency (< 3 kHz) and low amplitude (< 1 barg) calibration [5,10–13,16–18]. An ideal periodic calibrator would generate known pressures at a given frequency [2,4,5]. Lack of such accuracy is overcome by adding a reference pressure measurement in addition to the test sensor [2].

Kobata and Ooiwa [19] presented a square wave pressure generator using a rotating valve, which used air up to 1 barg and 1 kHz, reporting a well-shaped square wave at low frequencies. Hurst and Van De Weert [20] presented a spinning valve concept for the production of sinusoidal pressure signals. The valve had different holes interrupting a nozzle flow. The excitation range of the valve reached 2.8 kHz, for a pressure range between 0.068 barg and 0.689 barg, and a peak to peak pressure of 0.03 bar at maximum frequency. The calibrator was used to investigate the dynamic response of remote pressure transducers connected via flexible tubes to their measurement outlets. Whitmore et al. [17] used an oscillating piston and vacuum pump test rig, up to 2 kHz, for the same application.

The use of a liquid media allows the signal generators to reach higher amplitudes and frequencies, with the drawback of system contamination. Perls et al. [14] presented a sinusoidal pressure generator up to 10 kHz and with a peak to peak amplitude of 24 bars, using piezoelectric stacking with two working fluids, namely diphenyl metachloride and glycerol. Tsung and Han [21] introduced a square pressure wave generator using hydraulic oil as a working fluid with frequencies above 10 kHz and peak to peak amplitude up to 30 bara.

A dedicated study on the improvement of high frequency/amplitude periodic calibrators showed that siren type devices were the most promising solution to generate high amplitude pressure signal on a large range of frequencies [9]. It was also reported that sirens can produce periodic – not necessarily sinusoidal – low and medium pressure signals up to 1 kHz [22]. However, distortion of the generated signal into a saw-tooth like form was observed. Fridh et al. [23] reported pressure tap calibration up to 4 kHz using a reference pressure

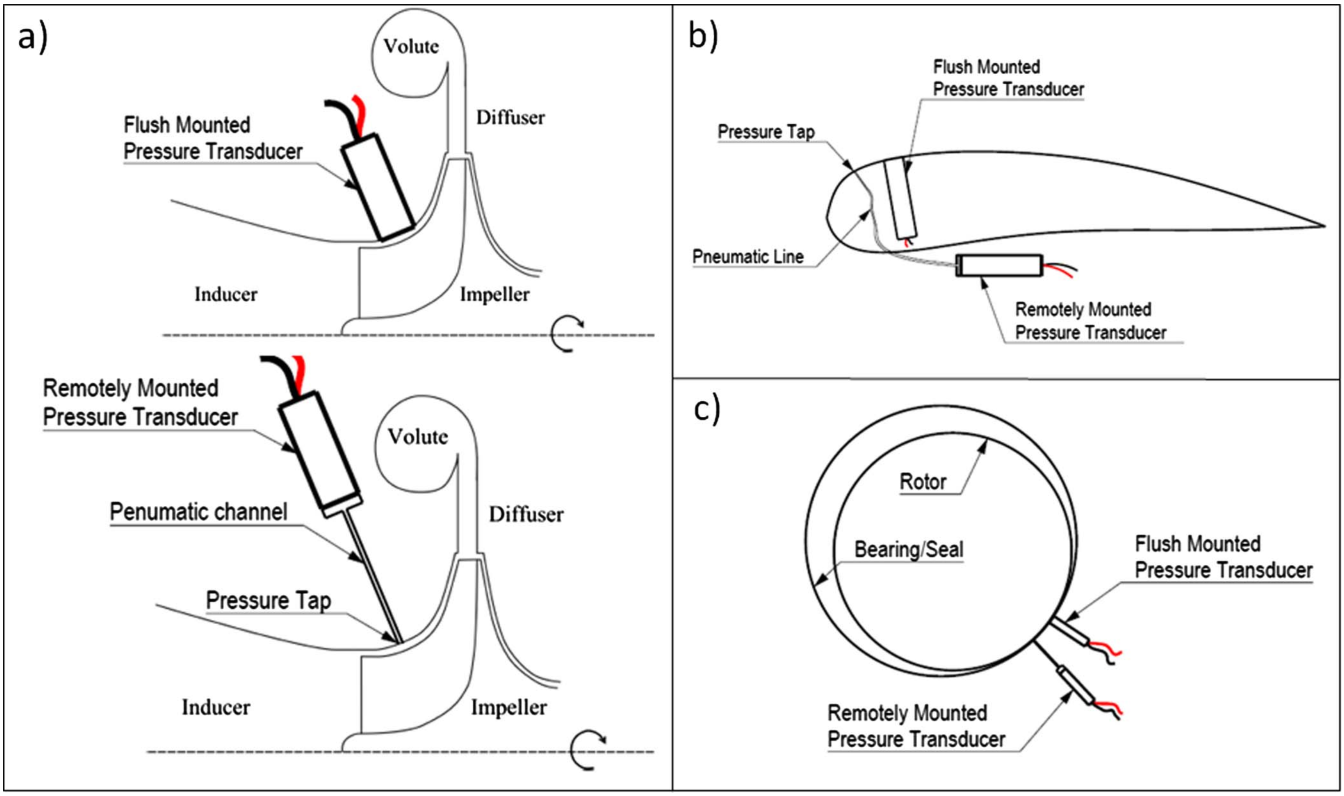

Fig. 1. Typical pressure sensor applications in engineering systems, (a) small scale turbomachinery, (b) external aerodynamics, (c) bearings and seals.