Experimental Analysis of a Waveguide Pressure Measuring System

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An infinite-line probe is commonly used to measure unsteady pressure in high-temperature environments while protecting the pressure transducer. In this study, an existing theoretical model is used to derive the response of a waveguide pressure measuring system. An ambient temperature centrifugal compressor rig acts as an experimental source of fluctuating pressure. The compressor is operated at different discrete rotational speeds, and the blade-passing frequencies are used to obtain frequency response data. In the experiments, pressure waves attenuated at a rate faster than that predicted by the theoretical model for a 0.322 m (12 in.) sensor offset. Furthermore, the decay in the magnitude of the pressure oscillations accelerated at blade-passing frequencies above 9 kHz. A unique contribution of this study is to show that whereas the experimentally observed overall attenuation is broadly consistent with the theoretical predictions, pressure oscillations corresponding to individual blade passages may be disproportionally attenuated. [DOI: 10.1115/1.3159387]

1 Introduction

The measurement of unsteady pressure is an integral part of experimental investigations pertaining to the design and development of gas turbine engines. As far back as 1971, Fischer [1] identified six major areas in engine development where unsteady pressure measurement plays a crucial role. Even today, the objectives could be as varied as studying engine noise [2], detecting and controlling thermo-acoustic instabilities in the combustor [3], detecting blade flutter, investigating compressor performance, or detecting compressor aerodynamic instabilities [4]. As the emphasis on areas such as condition based maintenance and resilient propulsion control grows, it may be necessary to measure pressure fluctuations in a production environment. In development or production, the key requirement is to ensure that the unsteady instrumentation operates reliably even in relatively harsh environments.

The advances in sensor technology over the years have led to improved high-temperature capabilities of a pressure sensor. However, this gain has been diminished by increased compression ratios and higher turbine inlet temperatures over the same span. Moreover, the reliability requirements of production environments are typically orders of magnitude higher than that of development testing. As such, the measurement of unsteady pressure in a high-temperature environment remains a challenging problem.

The solutions to high-temperature unsteady pressure measurement can be classified into at least three distinct categories: actively cool the sensor, design and develop sensors that can sustain even higher temperatures, or employ a waveguide to move the sensor away from the high-temperature environment. An actively cooled system can use water or air cooling to utilize existing sensors for high-temperature applications. However, active cooling adds bulk and mechanical complexity, while negatively impacting the measurement reliability.

There are some promising technologies currently at various stages of development that have the potential to yield sensors with significantly higher temperature capabilities. As an example, fiber-optic pressure sensors [5] have been demonstrated to operate at temperatures as high as 1050°C (1922°F). Another example is a plasma-based approach [6] capable of operating at temperatures as high as 1335°C (2400°F). However, the system uses a high voltage alternating current and the resulting electromagnetic radiation could interfere with surrounding equipment. For either techniques, challenges such as sensor packaging issues, high signal processing requirements, and unknown reliability need to be overcome before a production quality sensor can be built.

The acoustic waveguide approach has been in use for nearly 6 decades. An early example of its use is the study of combustion chamber screech by Blackshear et al. [7] in 1955. In a waveguide setup, also known as an infinite-line probe, a long and relatively narrow tube leads from the pressure measurement point. The sensor is mounted perpendicular to the tube axis at a distance from the high-temperature measurement location. The distance between the measurement point and the sensor location has a strong impact on the response of the waveguide and should be minimized subject to the temperature constraints. If the pressure sensor is mounted at the end of a short stem, the resulting cavity acts as a resonator and hence interferes with the measurement of unsteady pressure. As pressure waves reach the far end of the tube, visco-thermal dissipation along the tube ensures that the pressure oscillations attenuate and reflections are minimized.

A variety of theoretical models to understand the characteristics of remote pressure probes have been developed over the years. Iberall [8] was among the first to analyze the problem of the attenuation of pressure oscillations in instrumentation lines. The configuration was that of a pressure sensor at one end of a tube (short probe), where the other end is subjected to pressure oscillations. Bergh and Tijdeman [9] extended Iberall's work and developed an elegant analytical solution to the problem of pressure oscillations in N series connected tubes and volumes. Moreover, they experimentally validated the developed model by subjecting multiple configurations to pressure oscillations up to 200 Hz. Englund and Richards [10] applied the Bergh and Tijdeman model to the infinite-line probe configuration and illustrated the impact of key parameters. These include the tube inner diameter, length of the tube, distance of the sensor from the measurement end, and transducer cavity volume. Following up on the earlier work, Tijdeman [11] extensively analyzed the different analytical solutions pertaining to the propagation of sound waves in cylindrical tubes. Tijdeman [11] concluded that the propagation constant, i.e., the

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amplitude attenuation and phase change in sound waves for a given gas medium, is a function of two nondimensional parameters: the shear wave number and the reduced frequency. Richards [12] attempted to extend the theoretical model to tubes with noncircular cross sections, but concluded that a closed form solution was only possible for the case of symmetric, circular tubes. Furthermore, the author defined a generalized radius that can be used in the circular tube results to obtain reasonably accurate predictions for measurement systems with oval tubes.

The diverse application of unsteady measurement is evident in the diversity of the researchers that have characterized the response of pressure measurement systems. Nyland et al. [13] utilized a tunable whistle to experimentally determine the frequency response of short line probes. The same setup was later used by Richards [12] to demonstrate the validity of the modified Bergh and Tijdeman [9] model for predicting the response of a probe with an oval cross section. Salikuddin et al. [14] used broad spectrum noise to obtain the frequency response of an infinite-line probe microphone. Motivated by the need to measure unsteady pressures on hypersonic vehicles, Parrott and Zorumski [15] analyzed the impact of intense thermal gradients on the response of an infinite-line probe. In their experiments, the authors excited the system with pressure oscillations ranging from 400 Hz to 6 kHz and found a reasonable agreement between the predicted and observed system response. Ferrara et al. [16] and Straub et al. [17] also experimentally determined the response of an infinite-line probe. These two efforts obtained experimental results demonstrating a limited applicability of the theoretically estimated transfer function of the system.

The majority of the past efforts have been concerned with the frequency response of the infinite-line probe, i.e., the relationship of the actual versus the measured unsteady pressure amplitude as a function of its sinusoidal frequency. This knowledge is sufficient when the magnitude of a specific frequency, or the strength of a range of frequencies is of interest. A measure for compressor stability recently developed by Dhingra et al. [18] relates the repeatability of pressure time trace at blade-passing time scales to the stability margin of the compression system. This technique inherently requires the ability to capture the shape of the unsteady pressure variations over the tip of the compressor rotor. To this end, a centrifugal compressor rig at the School of Aerospace Engineering, Georgia Institute of Technology (Atlanta, GA) has been used to study an infinite-line pressure probe.

A unique contribution of this study is to show that whereas the experimentally observed overall attenuation is broadly consistent with the theoretical predictions, pressure oscillations corresponding to individual blade passages may be disproportionally attenuated. The resulting nonlinear distortion would render the waveguide pressure probe unsuitable for an application that requires a faithful representation of the shape of pressure fluctuations.

2 Facility

A centrifugal compressor rig (Fig. 1) at Georgia Tech has been used to study an infinite-line probe waveguide system. The compressor rig includes an inlet duct, a compressor, a discharge duct, a plenum, an exhaust duct, and a throttle. The setup has separate inlet and exhaust vents connected to the outside ambient air to prevent flow recirculation. The vents maintain compressor inlet conditions that are independent of exit flow conditions. The plenum is an aluminum chamber with a volume of approximately 1 m^3 and has a maximum pressure of 2758 kPa (400 psi). The flow exits the plenum through a duct connected to the exhaust vent. A butterfly valve in the connecting duct can be used to adjust the mass flow rate and vary the compressor loading.

The centrifugal compressor is a belt driven, variable speed supercharger compressor. Although the compressor is rated at 60 krpm, it is limited to 50 krpm for safety and to reduce maintenance. The compressor has seven full blades and seven splitter blades. A pressure tap is drilled in the compressor shroud between the full and splitter blades to mount either a pressure sensor or a waveguide tube.

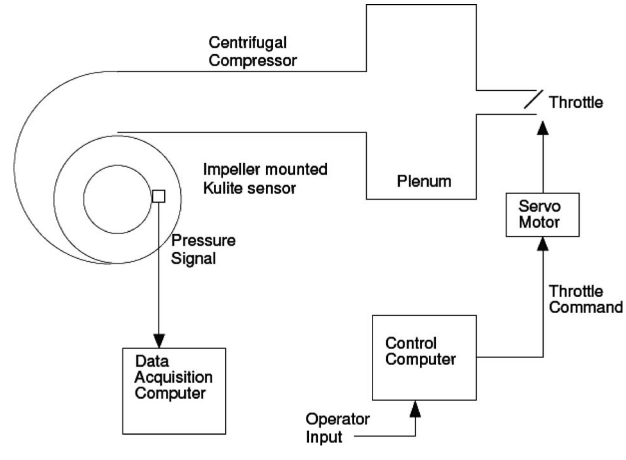

Fig. 1 Schematic of Georgia Tech centrifugal compressor setup

The waveguide system is equipped with two high bandwidth pressure sensors. The pressure sensors, manufactured by Kulite Semiconductor Products (Leonia, NJ), use a silicon-on-silicon Wheatstone bridge to measure pressure. The high natural frequency of the sensors (approximately 150 kHz) ensures that the pressure response bandwidth is only affected by the waveguide system geometry and not hindered by the sensors themselves.

The data acquisition computer is a dual processor desktop computer equipped with a National Instruments (Austin, TX) data acquisition card, AT-MIO-16E-1. The card features a 12 bit analog digital converter (ADC), with up to 16 single ended or 8 differential analog inputs.

2.1 Waveguide Setup. Figure 2 shows a schematic of the waveguide setup. A flexible polyurethane tube connects the pressure tap in the compressor shroud to the sensor location V_{v0}. A rigid metal tube connects the location V_{v0} to the sensor location V_{v1}. A 44.7 m long tube connected to location V_{v1} terminates the waveguide setup. For this study, two tube lengths between V_{v0} and V_{v1} have been tested: a shorter tube 0.178 m (7 in.) in length and a longer tube that is 0.322 m (12 in.) long. The pressure fluctuations generated by the passing blades travel via the flexible tube to the sensor located at V_{v0} and further to V_{v1}.

The pressure traces from sensors at V_{v0} and V_{v1} are used in this study to calculate the frequency response as well as to show the distortion effects. In either case, the mean pressure has been removed from the raw signal. The pressure ratio between the sensors is determined using Eq. (1). In order to obtain discrete experimental frequency values, the compressor speed is set to a range of fixed speeds. The blade-passing frequency is calculated from the pressure wave period, and each frequency data correspond to the blade-passing frequency.

$$\left|\frac{P_{v1}}{P_{v0}}\right| = \frac{\max(P_{v1}(t)) - \min(P_{v1}(t))}{\max(P_{v0}(t)) - \min(P_{v0}(t))} \tag{1}$$

3 Theoretical Analysis

As in many of the past studies, the analytical solution obtained by Bergh and Tijdeman [9] has been used in the present work to obtain the theoretical response of the waveguide setup. This model has been developed from the basic governing equations with the following simplifications.

- The mean gas properties are constant throughout a single element (tube or volume) of the measurement system.

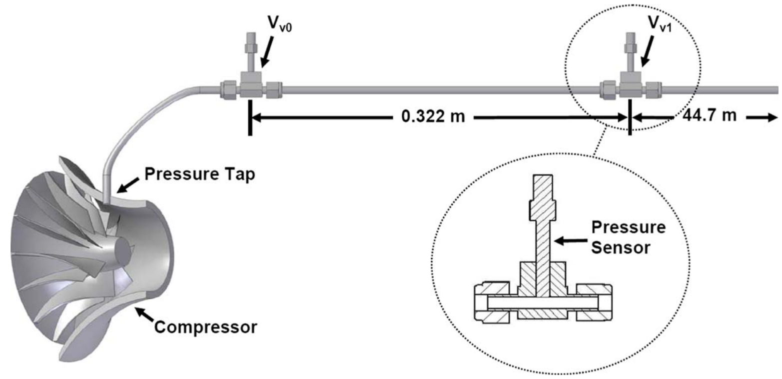

Fig. 2 A sketch of the waveguide experimental setup. The longer sensor offset (0.322 m) is shown here.

- Oscillation amplitudes are small relative to the respective mean values.
- The flow is laminar throughout the system.
- The internal radius of the tube is small.

It may be interesting to note that Englund and Richards [10] apparently relaxed the assumption of constant mean values to include mean temperature gradient (Fig. 5b in Ref. [10]) but did not present the associated analytical equations.

The key result of the Bergh and Tijdeman [9] model is included as Eq. (2) in the present work. Note that when $j=N$, the last two terms of this equation disappear.

$$\frac{p_j}{p_{j-1}} = \left[\cosh(\phi_j L_j) + \frac{V_{\nu_j}}{V_{t_j}}\left(\sigma_j + \frac{1}{k_j}\right) n_j \phi_j L_j \sinh(\phi_j L_j) + \frac{V_{t_{j+1}}}{V_{t_j}} \frac{\phi_{j+1}}{\phi_j} \frac{L_j}{L_{j+1}} \frac{J_0(\alpha_j)}{J_0(\alpha_{j+1})} \frac{J_2(\alpha_{j+1})}{J_2(\alpha_j)} \frac{\sinh(\phi_j L_j)}{\sinh(\phi_{j+1} L_{j+1})} \times \left\{\cosh(\phi_{j+1} L_{j+1}) - \frac{p_{j+1}}{p_j}\right\}\right]^{-1} \quad (2)$$

where

$$\alpha_j = i\sqrt{i} R_j \sqrt{\frac{\rho_{s_j}\nu}{\mu_j}} \quad \text{shear wave number}$$

$$n_j = \left[1 + \frac{\gamma - 1}{\gamma} \frac{J_2(\alpha_j\sqrt{P_r})}{J_0(\alpha_j\sqrt{P_r})}\right]^{-1} \quad \text{a polytropic factor}$$

$$\phi_j = \frac{\nu}{a_{0_j}} \sqrt{\frac{J_0(\alpha_j)}{J_2(\alpha_j)}} \sqrt{\frac{\gamma}{n_j}} \quad \text{propagation constant of the tube}$$

$$V_{t_j} = \pi R_j^2 L_j \quad \text{the volume of tube } j$$

Equation (2) shows that the ratio of the pressure at the jth volume to the pressure at the $(j-1)$th volume only depends on the characteristics of the system downstream of the $(j-1)$th volume. In other words, the transfer function from the $(j-1)$th volume to the jth volume does not depend on the tubes and volumes upstream of the $(j-1)$th volume. In terms of the specific application to the system under study (Fig. 2), the relationship between oscillations at V_{v1} and V_{v0} depends only on the geometry downstream of the volume V_{v0}. Consequently V_{v0} can be considered as the "source" for the purpose of this work.

The distance between the two sensor volumes, here referred as "sensor offset" and denoted by L, significantly impacts the pressure measured at location V_{v1}. The length of the termination tube, 44.7 m, is long enough that it is expected to provide a reflection free or anechoic boundary condition. The magnitude results of the calculated response presented in Fig. 3 illustrate this point. The absence of any resonance peaks in the magnitude response, irrespective of the value of the sensor offset, signifies that there are no reflections from the far end of the tube. Furthermore, the impact of sensor offset is as may be expected: The longer the distance between the source and the sensor, the larger the attenuation at a given frequency.

The inner radius of the tube is another geometric parameter of significance. As illustrated by the results in Fig. 4, the smaller the tube diameter, the larger the dissipation at a given pressure oscillation frequency. As the theoretical model is valid for small values of tube radius, the prediction for large values of R should be treated with caution. Nevertheless, using tubes of a larger radius can increase the measurement bandwidth of the system.

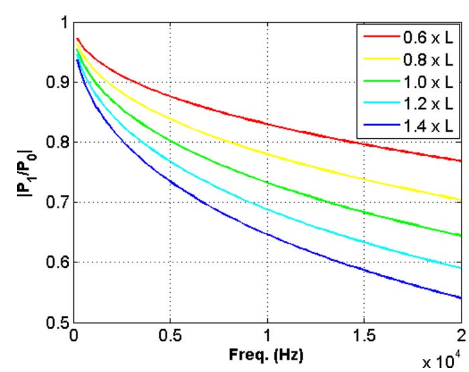

Fig. 3 Theoretical bandwidth predictions with varying transducer offset length. The nominal value of offset *L* is 0.322 m.

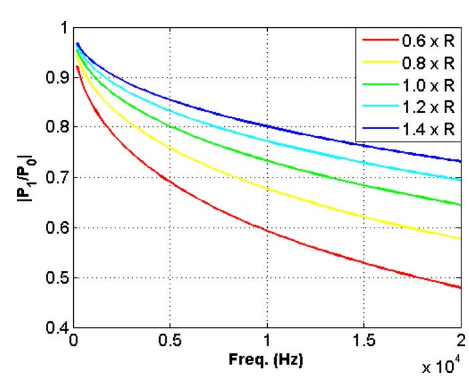

Fig. 4 Theoretical bandwidth predictions with varying waveguide radius

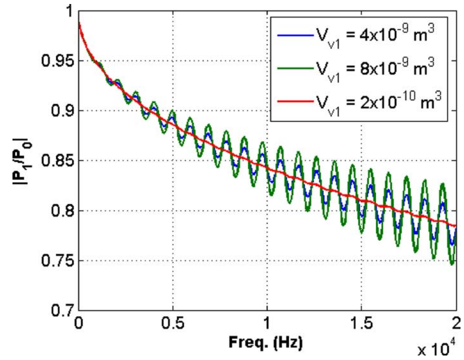

Fig. 5 Pressure transducer volume comparisons

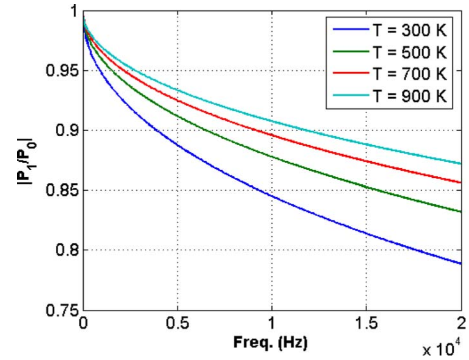

Fig. 6 Theoretical bandwidth predictions with varying temperature

The results of the waveguide response presented so far have been calculated with the assumption that the transducer is mounted flush to the interior of the tube, and hence the volumes V_{v0} and V_{v1} are zero. To illustrate the impact of nonflush sensors, the waveguide response for three transducer cavity volumes has been calculated. The results presented in Fig. 5 show that, on average, the signal decays at the same rate irrespective of the cavity volume. However, except for the smallest volume case, the nonzero transducer cavity results in resonant peaks that are a periodic function of the pressure fluctuation frequency. For the current setup, 1 mm offset would result in a transducer cavity volume of 11 mm^3. However, in the following analysis of the experimental results, it is assumed that this volume is zero. The actual transducer cavity volume for the setup, though not zero, is expected to be of the order of 0.2 mm^3, the smallest volume of the results in Fig. 5.

3.1 Impact of the Mean Air Temperature. It is possible to obtain an analytical expression for the sensitivity of the system to variations of mean temperature under some simplifying assumptions. Specifically, it is assumed that gas properties such as absolute viscosity, thermal conductivity, and specific heat ratio are independent of temperature. This assumption is not rigorously accurate, but the aforementioned properties are weak functions of temperature and can be neglected for low order analysis. The general solution of pressure perturbation in a tube can be expressed as (Eq. (36) of Ref. [9])

$$p = Ae^{\phi x} + Be^{-\phi x}$$

Essentially, the pressure at any location x is the sum of two characteristic waves, one traveling along the positive x-direction, and the other along the negative. The coefficients A and B are determined by the boundary conditions. Assuming a nonreflecting downstream boundary, the coefficient B can be set equal to 0. Then the sensitivity with respect to mean temperature is given by

$$\frac{\partial p}{\partial T_s} = A\frac{\partial e^{\phi x}}{\partial T_s} = \phi A e^{\phi x}\frac{\partial \phi}{\partial T_s} = -\frac{\phi^2}{2T_s}Ae^{\phi x} = -\frac{C_1}{T_s^2}Ae^{\phi x}$$

where

$$C_1 = \frac{\nu}{\gamma R_{\mathrm{air}}}\frac{J_0(\alpha)}{J_2(\alpha)}\frac{\gamma}{n}$$

Hence, the response of the infinite-line probe is weakly dependent on the mean temperature of fluid medium. Further, the sensitivity decreases with increasing temperature. The magnitude of the calculated pressure ratios for different mean temperature values shown in Fig. 6 reiterates this point. It may be noted that these results have been calculated using the full recursive relation (Eq. (2)). The mean temperature at the pressure port of the compressor rig used for this work is close to ambient temperature. The typical application of a waveguide is for high-temperature pressure measurement: rear stages of a high pressure compressor, combustor, or turbine. The preceding analysis demonstrates that the waveguide response obtained using the low temperature rig is indicative of its response under high-temperature conditions. It is emphasized that if the termination tube is of insufficient length, the lower decay rate of pressure oscillations at high mean temperatures could lead to resonant peaks.

Although the results presented here have concentrated on the magnitude of the response, a phase lag is also present in the waveguide arrangement. In general, this difference in the phase of the unsteady pressure and that measured by the sensor may be a nonlinear function of its frequency. However, for the nonreflecting conditions, as in the present work, the phase is a linear function of frequency. In this case, the phase difference is due to the finite time taken by the pressure signal to travel from the source to the sensor location. This propagation delay, τ, is given by

$$\tau = \frac{L}{a} \tag{3}$$

where L is the distance between the desired measurement location and the sensor location, i.e., the distance between volume V_{v0} and V_{v1}. For completeness, the speed of sound a is

$$a = \sqrt{\gamma R_{\mathrm{air}} T} \tag{4}$$

where γ is the ratio of specific heats, R_{air} is the universal gas constant for air, and T is the temperature.

4 Frequency Response Results

The theoretical analysis shows that the tube inner radius is a key geometric parameter governing the response of the waveguide system. In the current work, no effort has been made to obtain precise measurements of this parameter. Furthermore, manufacturing tolerances as well as deformation during installation may introduce nonuniformity in the tube cross section. Finally, Bergh and Tijdeman [9] pointed out that when boundary layer effects are considered, the effective radius of the tube could be less than its actual value. Despite these limitations, at least as far as the frequency response is concerned, the following results show that the theoretical results are largely representative of the practical system.

In order to gauge the impact of sensor offset, two lengths have been tested and are discussed in the following analysis. The shorter tube has a length of 0.178 m (7 in.), whereas the longer tube is 0.322 m (12 in.) long. As described in the experimental setup earlier, the discrete frequency points are obtained by operating the compressor at fixed shaft speed settings. As data are acquired at 2 krpm intervals, the discrete points are 467 Hz apart.

The results of the shorter tube are compared with the corresponding theoretical prediction in Fig. 7. As evident in this figure, the experimentally observed pressure amplitude ratio is in broad agreement with the predicted values. An exception is the peak that can be observed in the 4–5 kHz range. As this peak is present in

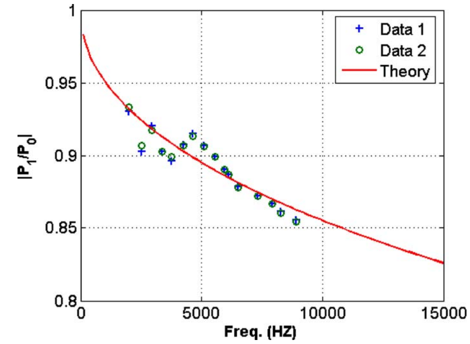

Fig. 7 Theoretical and experimental results comparison for 0.178 m (7 in.) transducer offset

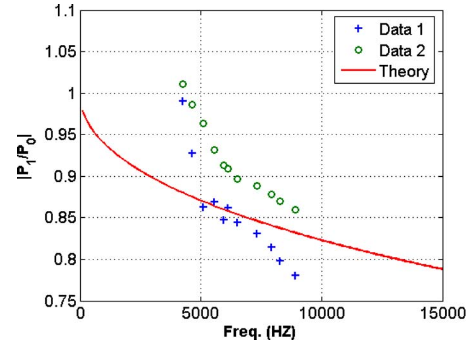

Fig. 9 Theoretical and experimental results comparison for 0.178 m (7 in.) transducer offset while beginning measurement sequence at 4.26 kHz (twice the lowest rotational speed

two independent sets of experiments, labeled as "Data 1" and "Data 2," respectively, it may be concluded that it is a repeatable feature of the waveguide arrangement.

The results for the longer tube (0.322 m) are shown in Fig. 8. In this case, the experimental results are broadly consistent with theoretical prediction for pressure oscillations of up to 8.0 kHz. The theoretical losses are slightly overpredicted for blade-passing frequencies less than 7.3 kHz. The experimental results sharply diverge from their theoretical counterpart as the exciting frequency increases beyond 8 kHz. From the trend observed, it may be concluded that the pressure measurement bandwidth for the longer tube is around 9 kHz.

The next set of results emphasizes the need for a thorough calibration of any waveguide system prior to its application. The preceding results have been obtained by a sequence of experiments where the compressor was operated over a range of speeds starting at 10,000 rpm. For the shorter tube case, it has been observed that the waveguide responds differently when the sequence started at 20,000 rpm. In either case, speeds were incremented in steps of 2000 rpm. The results are summarized in Fig. 9. The tendency of the response to peak between 4 kHz and 5 kHz range is significantly magnified in this case. To rule out a bad data set, the experiments have been repeated multiple times, and on different days, but with similar results. To date, the cause for this behavior has not been determined. Although this behavior may be specific to the facility used, it highlights the potential pitfalls of a waveguide configuration.

5 Time Domain Results

An accurate measurement of the pressure shape at blade passage time scales could be critical to a novel compressor stability detection approach [18,4]. A time domain analysis of the waveguide pressure recordings shows that the frequency response characteristics may not be sufficient to describe this aspect of a waveguide pressure measurement.

At lower fundamental frequencies, for the shorter sensor offset case, the waveguide has a minimal impact on the pressure measurement. The raw pressure traces of Fig. 10 show that the only significant part of the waveguide response is a phase difference between the pressure measured at V_{v0} and V_{v1}. As mentioned earlier, this phase difference can be characterized by a constant propagation delay. In the sequel, the traces of the pressure measured at V_{v1} have been shifted in time by the delay constant τ (Eq. (3)), which essentially corrects for the phase differences.

At moderate driving frequencies, apart from minor distortions, the pressure measured by the sensor at V_{v1} faithfully reproduced the shape of the pressure oscillations. This is illustrated by the time traces for 2.8 kHz blade-passing frequency, shown in Fig. 11. It may be observed in this figure, that some of the details of positive part of the pressure cycle are obscured by the waveguide response. However, the pressure measurements retain the sharp vertices at the trough of each cycle.

At higher frequencies, the results are not very encouraging even for the shorter tube. The results for the 9.3 kHz blade-passing frequency show that the waveguide filters part of the pressure oscillations. As evident in Fig. 12, the peak of each pressure cycle has been smoothed by its passage through the waveguide. However, the troughs remain distinctly sharp. Furthermore, the low frequency modulation of the pressure amplitude present at V_{v0} is not transmitted to V_{v1}.

The limitations of the waveguide pressure measurement setup in reproducing the shape of the pressure oscillations is perhaps more apparent in the results of the larger sensor offset. At moderate blade-passing frequencies the response of the waveguide with the longer offset is similar to the shorter offset. The time traces for

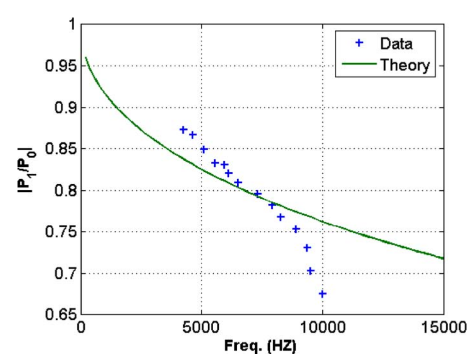

Fig. 8 Theoretical and experimental results comparison for 0.322 m (12 in.) transducer offset

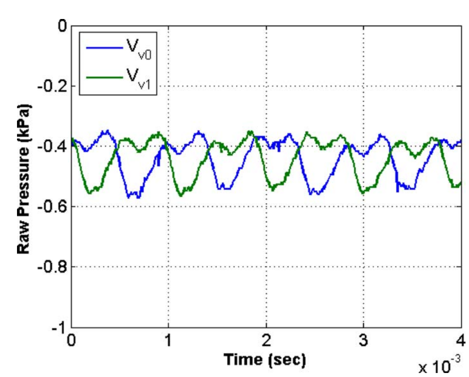

Fig. 10 Raw pressure time trace for 1 kHz blade-passing frequency

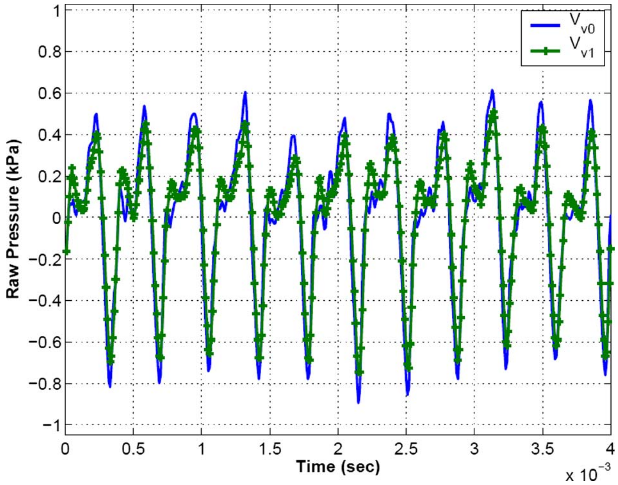

Fig. 11 Pressure response for 2.8 kHz blade-passing frequency

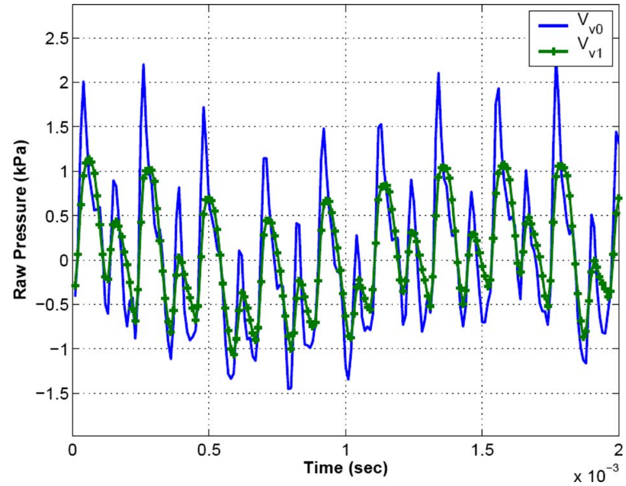

Fig. 13 Experimental pressure response for 2.8 kHz blade-passing frequency after V_{v0} is shifted to account for time delay with 0.322 m between sensors

2.8 kHz blade-passing frequencies in Fig. 13 show that the pressure at V_{v1} only differs from that at V_{v0} near the peak of the cycle. The overall shape of the pressure fluctuation is captured.

The time traces for blade-passing frequency of 9.3 kHz have been presented in Fig. 14. The shape of the pressure oscillations measured at V_{v1} is significantly different from that at V_{v0}. Most of the features visible in the latter are missing in the former. Unlike the shorter offset case, no smoothing of the pressure can be observed. Although the relatively high attenuation in this case is not unexpected, some cycles are disproportionately diminished.

6 Conclusions

A pressure waveguide is a device frequently employed when measuring unsteady pressures in harsh environments. This device enables the remote measurement of pressure fluctuations while protecting the sensor from exposure to high temperatures. An available analytical model can be utilized to design waveguide systems. The experimental results show that, to a limit, this model accurately predicts the frequency response of a waveguide setup. However, it may not sufficiently characterize the time domain distortion of the signal.

Waveguides limit the pressure sensing bandwidth, may introduce resonant peaks, and distort signals in an unpredictable way. Although effective for some, they are not suitable for all gas turbine applications. In particular, the shape of the pressure time trace may not be faithfully transmitted by a pressure waveguide. In cases where the shape of a pressure waveform is of interest, e.g., validation of a time accurate unsteady computational fluid dynamics (CFD) solver, flush-mounted sensors should be preferred over waveguide installations.

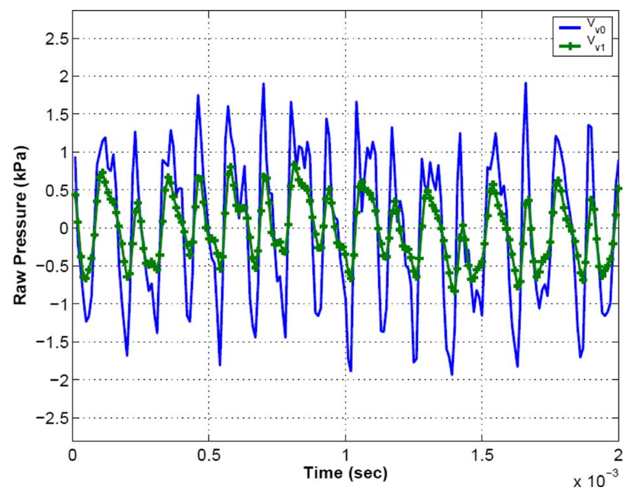

Fig. 14 Experimental pressure response for 9.3 kHz blade-passing frequency after V_{v0} is shifted to account for time delay with 0.322 m between sensors

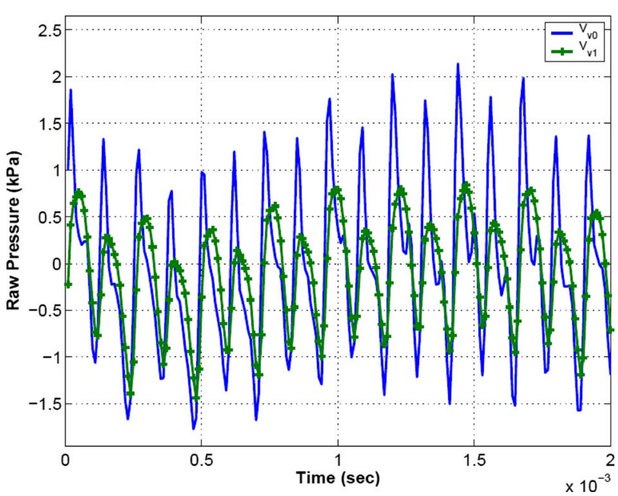

Fig. 12 Pressure response for 9.3 kHz blade-passing frequency

Nomenclature

a = mean velocity of sound
g = gravity constant
i = imaginary unit
J_n = Bessel function of first kind of order n
k = polytropic constant for the volumes
L = tube length
n = polytropic constant
N = number of tubes and volumes
p = input pressure amplitude
P_r = Prandtl number
R = tube radius
R_{air} = gas constant for air
V_v = pressure transducer volume

V_t = tube volume
α = shear wave number
γ = specific heat ratio
λ = thermal conductivity
μ = absolute fluid viscosity
ν = frequency
ρ_s = mean density
σ = dimensionless increase in transducer volume due to diaphragm deflection
ϕ = dissipation function

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