TUBE RESPONSE LINEARISATION

TFI's instrumentation accurately measures dynamic pressure by correcting the distortions caused by tubes used to connect pressure measurement points to pressure transducers. This process is called linearisation.

WHY IS LINEARISATION REQUIRED?

Time-varying (dynamic) pressure is commonly measured by sensing the pressure fluctuations at the end of pressure tubes that connect the measurement points (often called taps) to pressure transducers. Amplitude and phase distortions, caused by viscous forces and other effects, are introduced into the pressure fluctuations as they propagate along the tubing. If these amplitude and phase distortions are not corrected for, the resulting time-varying pressure signal will be incorrect.

Time-averaged (static) measurements do no require linearisation, as the amplitude and phase distortions do not affect the mean pressure value measured over a sufficient length sample time.

WHAT FACTORS AFFECT AMPLITUDE & PHASE DISTORTIONS?

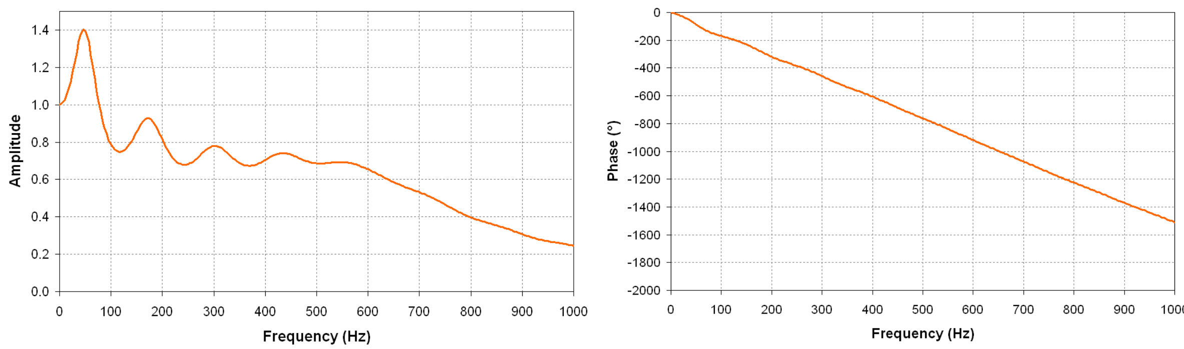
The distortions introduced into the pressure fluctuations mainly depend on the tube length and diameter of *all* sections of the tubing from the measurement point to the pressure transducer diaphragm. This includes the transducer internal volume, as well as any changes in tubing internal diameter introduced by the use of pressure ports and restrictors.

HOW IS LINEARISATION PERFORMED?

In order to linearise a measured pressure signal, it is necessary to know the frequency response function (transfer function) of the tubing being used.

Tubing Frequency Response Function

Transfer functions are complex functions used in signal processing and can be visually interpreted by viewing the absolute (amplitude) and angular (phase) parts of the function, as shown in the figure below. This figure shows that the fluctuation amplitude can be both amplified and attenuated across the frequency range, while the time delay (phase lag) increases with frequency. Linearising a pressure signal corrects these distortions.



A frequency response function for 1200 mm of 1.2 mm ID tubing attached to a TFI Dynamic Pressure Module (includes the effects of module internal tubing and transducer volume).

A tubing frequency response function can be either theoretical or experimental. Theoretical or numerical estimations of the transfer function are calculated using the theory developed by Bergh and Tijdeman (see References below) and require knowledge of the length and internal cross-sectional area of all tubing used, as well as the ported volume of the pressure transducers. A theoretical function can be generated by the *TFI Device Control* software's *Frequency Response Calculator*.

Correcting the Pressure Signal

There are several methods of linearising the response of pressure tubing. The method used with TFI's instrumentation involves three steps:

1. convert the time domain pressure data to the frequency domain;
2. divide by the transfer (frequency response) function of the pressure tubing;
3. convert the linearised frequency domain data back to the time domain.

Conversion between the time and frequency domains is performed using forward and inverse fast Fourier-transforms (FFTs). Initial conversion to the frequency domain provides a frequency spectrum of the pressure signal, which is then corrected using the complex transfer function of the pressure tubing. The corrected pressure spectrum is then returned to the time domain using an inverse FFT.

The actual process is somewhat more complex than this, as data must be processed in blocks, in real-time, as they are acquired. Extra processing is also performed to improve the overall accuracy of the pressure signal. However, the principles of the procedure are as outlined above.

Effective Simultaneous Sampling

At the same time that linearisation of the pressure signal is occurring, corrections are also made to account for the inter-channel sampling delays caused by sampling multiple channels sequentially. This means that once the corrected pressure data are returned to the time domain, the data from multiple channels (e.g. in a Dynamic Pressure Module) are effectively simultaneously sampled.

THE CORRECTED PRESSURE SIGNAL

In order to show the effectiveness of linearisation, some sample data was taken with the set-up given in the following table.

Table 1: Sample data instrumentation set-up

Instrumentation	Sample data: 64-channel Dynamic Pressure Module Reference data: precision microphone
Tubing	1200 mm x 1.2 mm ID + DPM internal tubing
Sampling rate	5 kHz/channel*
Channels used	Sample data: 1st channel Reference data: 65th channel**
Filtering	All data low pass filtered at 1 kHz
Tube frequency response function	Experimentally generated

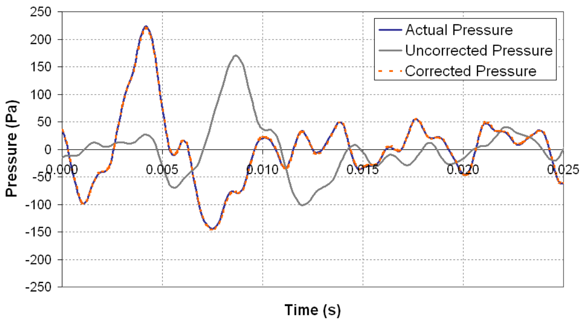
* During this test the total channel count was effectively 128, therefore the data conversion rate was 128*5000 = 640 kHz (i.e. overall data acquisition rate)

** With a 640 kHz data conversion rate, this gives a ~36° sampling phase lag at 1 kHz *before* correcting for inter-channel sampling delays

TurbulentFlow Instrumentation

This data was then linearised using the procedure detailed above and the results are plotted in the figure at right.

The figure shows how effectively a fluctuating pressure signal can be recreated by applying the appropriate tube response function. The sample pressure fluctuations included significant components up to 1 kHz, yet after linearisation the corrected pressure is within 2% of the actual pressure,, compared to 30% amplitude error and a large phase error for the uncorrected pressure.



Sample data showing the importance of linearisation (the corrected pressure is within 2% of the actual pressure, compared to 30% amplitude error for the uncorrected pressure).

These results are particularly good because of the experimentally generated tubing frequency response function used to generate them. However, in most situations a theoretically generated function is more than adequate, as long as the tubing characteristics (such as length and internal diameter) are accurately known. If an accurate frequency response function is not used, the resulting frequency content of time-varying pressure fluctuations will be incorrect.

Accurate Results

The corrected data are a more accurate representation of the actual pressure at any instant of time, and have more accurate statistical measures such as peak pressure and standard deviation (see Table 2 below). This allows correlations with other events and calculations, such as wind loadings, to be performed accurately.

Table 2: Statistical measures for the Actual, Uncorrected and Corrected Pressure signals for the example given in the previous figure (the percentage error compared to the Actual Pressure is given in brackets)

	Standard Deviation (Pa)	**Peak +ve Pressure (Pa)**	**Peak –ve Pressure (Pa)**
Actual Pressure	64.3	268.6	-265.4
Uncorrected Pressure	49.8 (-23%)	185.7 (-31%)	-214.1 (-19%)
Corrected Pressure	64.5 (+0.3%)	262.7 (-2%)	-268.4 (+1%)

References

H. Bergh & H. Tijdeman, “Theoretical and experimental results for the dynamic response of pressure measuring systems”, National Aero and Astronautical Research Institute, Amsterdam, Report NLR-IRF. 238, 1965.

For Further Information

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