NOTES ON WIND TUNNEL TESTING
Revision A

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Figure 1. Falcon 9 Wind Tunnel Model (courtesy Space-X)

Introduction

Aerospace vehicle scale models are subjected to wind tunnel testing for a number of reasons, including the measurement of

1. Flutter behavior of airfoils.
2. Lift, drag, lateral forces, yaw, roll, and pitching moments over a range of angles of attack.
3. Fluctuating pressure loads from laminar flow, turbulent boundary layers, flow separation and reattachment, shock waves, vortex shedding, etc.
4. Effect of protuberances, appendages, boat-tail sections, vents, cavities, surface roughness, etc.

This tutorial is primarily concerned with the third objective. The fluctuating pressure loads tend to be greatest when the airflow is transonic. The maximum dynamic pressure condition is another case of interest.

Furthermore, the airflow speed may remain constant during a test run, or it may be increased for a "Mach sweep." The Mach sweep is more realistic for rockets and missiles. A constant Mach number test would tend to yield higher pressure levels.

Variables

D	Diameter
f	Frequency
q	Dynamic pressure
U	Free stream air flow velocity
FPL	Fluctuating Pressure Level
SPL	Sound Pressure Level

Note that the FPL and SPL are similar. The distinction is that an SPL tends to imply a diffuse sound field, where the sound energy is spread evenly over a space.

Scaling

The scale models must be precise in terms of geometry, mass, and stiffness distribution.

The fluctuating pressure is scaled as

$$FPL_{flight} = FPL_{tunnel} + 20\log_{10}\left(\frac{q_{\,flight}}{q_{\,tunnel}}\right), \quad \text{dB} \quad \text{re } 20\ \mu\text{Pa} \tag{1}$$

The frequency is scaled according to the Strouhal numbers as

$$\left(\frac{f\,D}{U}\right)_{flight} = \left(\frac{f\,D}{U}\right)_{tunnel} \tag{2}$$

As an example, consider that the flight and tunnel airflow velocities are equal. Now assume that the wind tunnel model is 5% scale, or 1:20, with respect to diameter. The following table shows the conversion from wind tunnel to flight frequencies.

1:20 Scale Model	
Wind Tunnel Freq (Hz)	Flight Freq (Hz)
100	5
500	25
1000	50
2000	100
5000	250
10K	500
20K	1000

Frequency Limitations

The dynamic pressure is typically measured using Kulite pressure transducer. The sensor's frequency response depends in part on its mounting configuration. The frequency response determines the maximum frequency that can be accurately measured.

In addition, the sample rate must be set high enough to capture the maximum frequency of interest. Proper analog anti-aliasing filters must be used prior to digitization. Further guidelines are given in Reference 1.

Noise Sources

Wind tunnels have noise sources from

1. Blade passing tones
2. Wall slot tones
3. Tunnel cavity acoustical tones
4. Shock reflections
5. Strut wakes
6. Vortex shedding

These noise sources can affect the pressure measurements at the model surface. The noise must be removed from the measurements as a post-processing step.

A good approach is thus to perform an "empty tunnel test" to characterize the noise sources, prior to the scale model test.

Reynolds Number

The Reynolds number Re is a dimensionless number that gives a measure of the ratio of inertial forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions.

Note that the Reynolds number Re is defined as

$$Re = UL/\nu \tag{3}$$

where

L	=	Reference length or diameter
U	=	Free stream velocity
ν	=	Kinematic viscosity

Air has the following kinematic viscosity under normal conditions per Reference 2.

$$\nu \cong 1.6\ (10^{-4})\ \mathrm{ft}^2/\mathrm{sec}$$

The Reynolds number is a particular challenge in wind tunnel testing.

Osborne Reynolds (1842-1912) discovered that if the same atmospheric pressure was used for experiments with wind tunnel models as a full-size aircraft would encounter under actual conditions, then the experimental results would be invalid.

The Reynolds number needs to be the same under wind tunnel conditions that it is under regular atmospheric conditions, in order for the test to be valid.

The way to ensure this is to increase the air density inside the tunnel by the same proportion as the model is smaller than the full-size aircraft. Thus, if a model is 1/10 the size of a full-size aircraft, then the air density inside the tunnel must be increased by a factor of 10 in order to achieve wind tunnel results that are valid for a full-size aircraft in regular atmospheric conditions.

References

1. Notes on Sample Rate and Aliasing, Revision A, Vibrationdata, 2007.

2. I. Shames, Mechanics of Fluids, McGraw-Hill, New York, 1982.