The Statistical Nature of Unsteady Inlet Flow

Bernhard H. Anderson
NASA Glenn Research Center
Cleveland, Ohio, 44135

Statistical Nature of Unsteady Inlet Flow

"The understanding and analysis of the unsteady information obtained from LES and DES analyses is fundamentally different from steady Reynolds Averaged Navier Stokes (RANS) analysis. That is because the process described by unsteady analyses is fundamentally stochastic in nature and not deterministic. The basic feature of the probability theory, or more commonly the statistical approach, is the transition from the consideration of a single turbulent flow within the inlet, to the consideration of a statistical ensemble of all similar turbulent flows created by the inlet. Thus the only possible description of the turbulent flow within the inlet is a statistical description based on the study of specific statistical laws, i.e. "the theory of random fields" (1)

(1) Monin, A. S., and Yaglom, A. M., "Statistical Fluid Mechanics", The MIT Press, Cambridge, Massachusetts, 1971.

Statistical Nature of Unsteady Inlet Flow Stochastic Processes

Stationary processes are unsteady flows which are statistical stable with probabilistic properties that do not change over time, in particular varying about a fixed mean level and with constant variance.

Non-Stationary processes are unsteady flows which exhibit no natural mean level over time and contain both coherent and random variations in their unsteady flow field structure.

Statistical Nature of Unsteady Inlet Flow Homogeneous Random Processes[1]

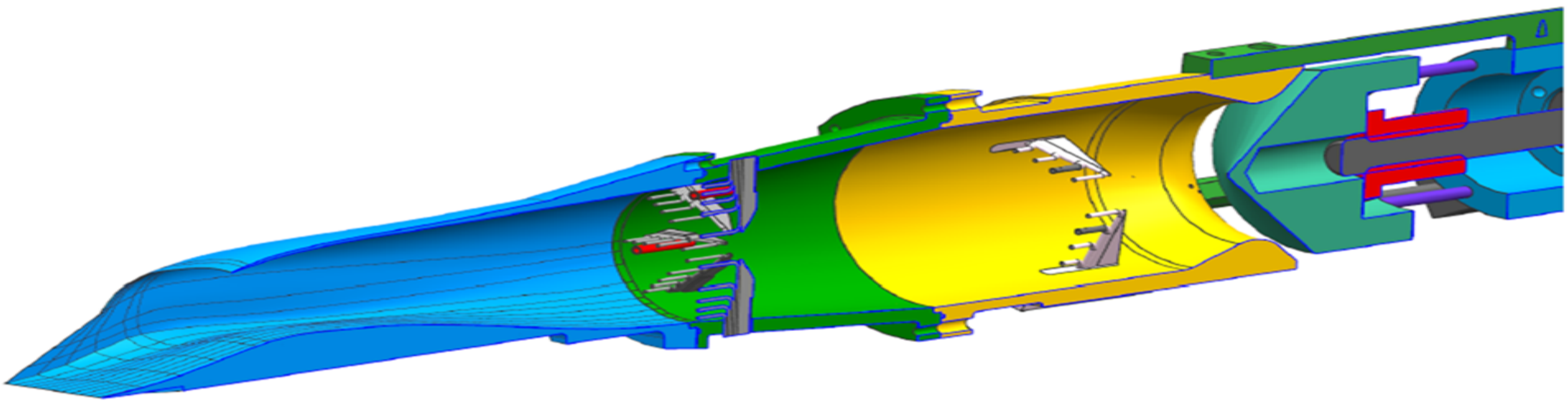
"Many time series actually encountered in aerodynamics exhibit non-stationary behavior and in particular do not vary about a fixed mean. Such series nevertheless exhibit homogeneous behavior over time of a kind. In particular, although the general level about which fluctuations are occurring may be different at different times, the broad behavior of the series, when differences in level are accounted for, may be similar over time. This behavior may be modeled in terms of an autocorrelation operator."[2]

(1) To detect coherent structures in data containing random variations.

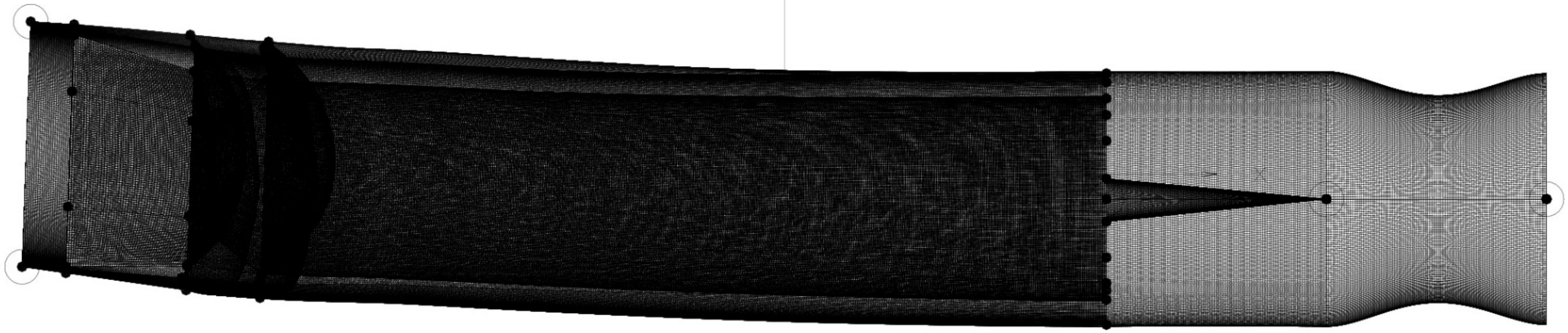
(2) To identify an appropriate time series model for the mean if the data is non-stationary.

(1) George, W. K.: "Lectures in Turbulence for the 21st Century", January, 2013
(2) Box, E. P., Jenkins, G. M., and Reinsel, G. C.: "Time Series Analysis", John Wiley & Sons, 2008.

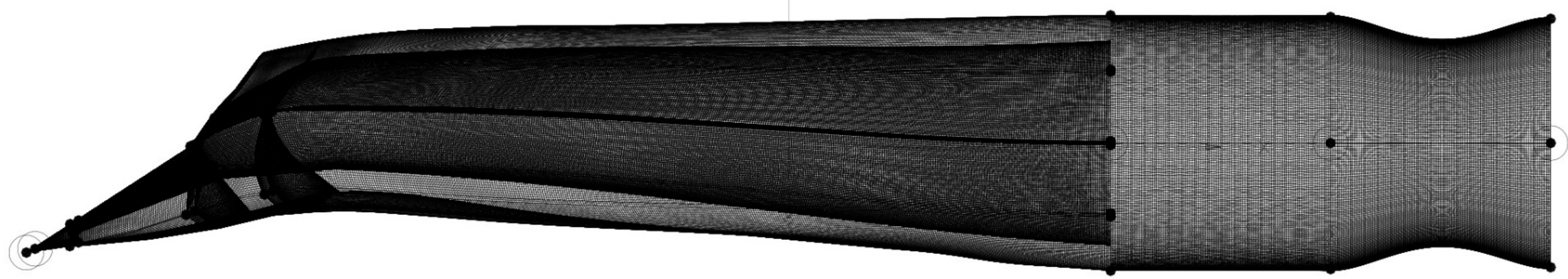
Boeing QEVC Low Boom Supersonic Inlet Design
8x6 NASA/GRC SWT



Boeing QEVC Low Boom Supersonic Inlet Design
Computational Grid = 32.945×10^6
Number of Blocks = 151



Top View



Side View

Boeing QEVC Low Boom Supersonic Inlet Design
Inlet Scale Information

Model	Acap (sq. in.)	Daip (in.)	Actual Scale	Approx. Scale
Test Scale	1.5631	1.5361	0.0231	1/43
Ref. Scale	381.57	24.0	0.3692	1/3
Full Scale	2802.0	65.0	1.0	1/1

Boeing QEVC Low Boom Supersonic Inlet Design 8x6 SWT Conditions for Test

Variable	*Value*
Tunnel Mach Number, M_0	*1.560*
Tunnel Total Pressure (lbs/ft²), P_o	*2942.9*
Tunnel Total Temperature (°R), T_o	*627.0*
Reynolds Number, Re_{Daip}	*6.275×10^5*

Boeing QEVC Low Boom Supersonic Inlet Design Response Variables

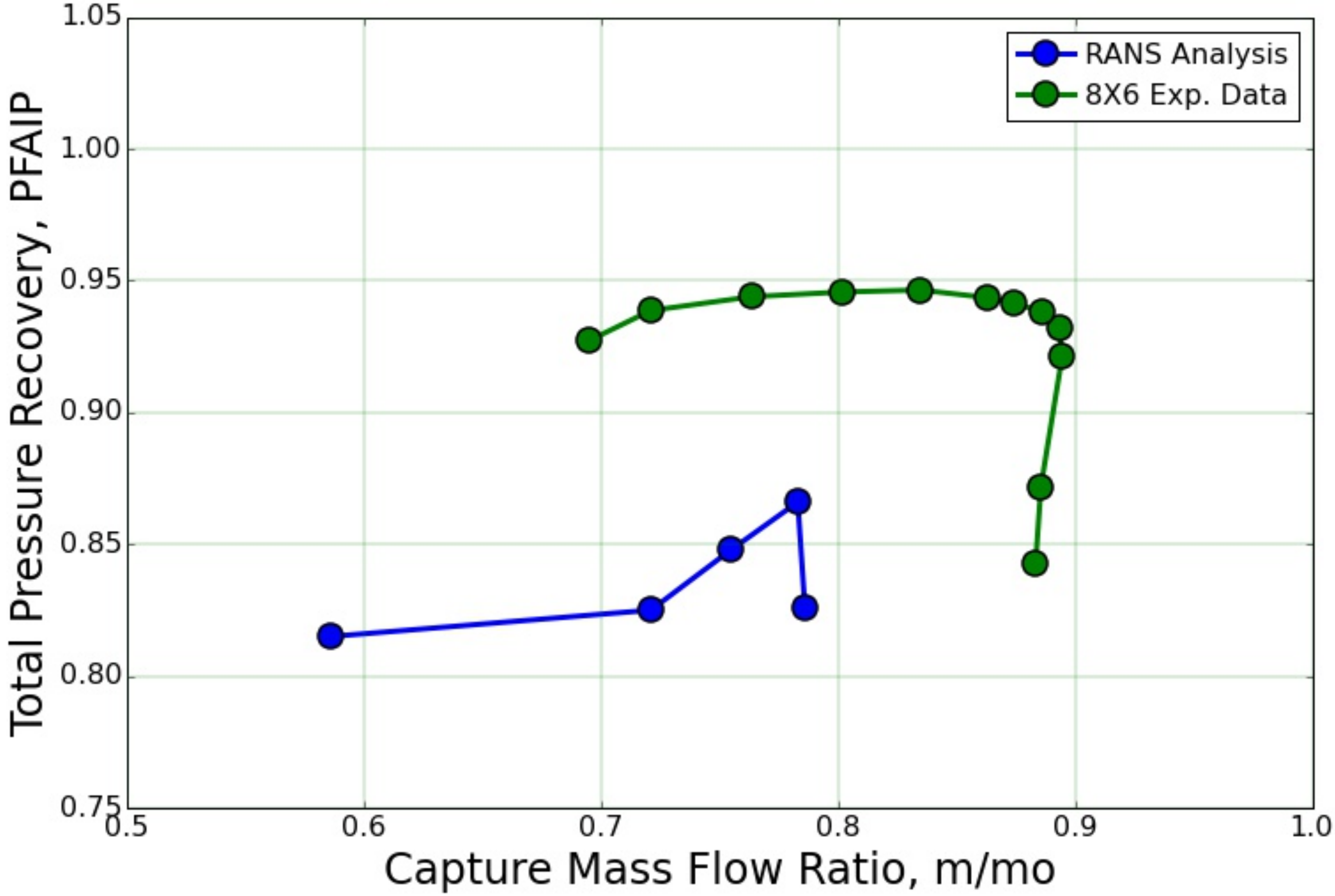
Response Variable	Symbol
Area Averaged Capture Mass Flow	m/m_0
Area Averaged AIP Total Pressure Recovery	PFAIP
AIP Circumferential Distortion	DPC/P

Boeing QEVC Low Boom Supersonic Inlet Design Time Relevant Variables

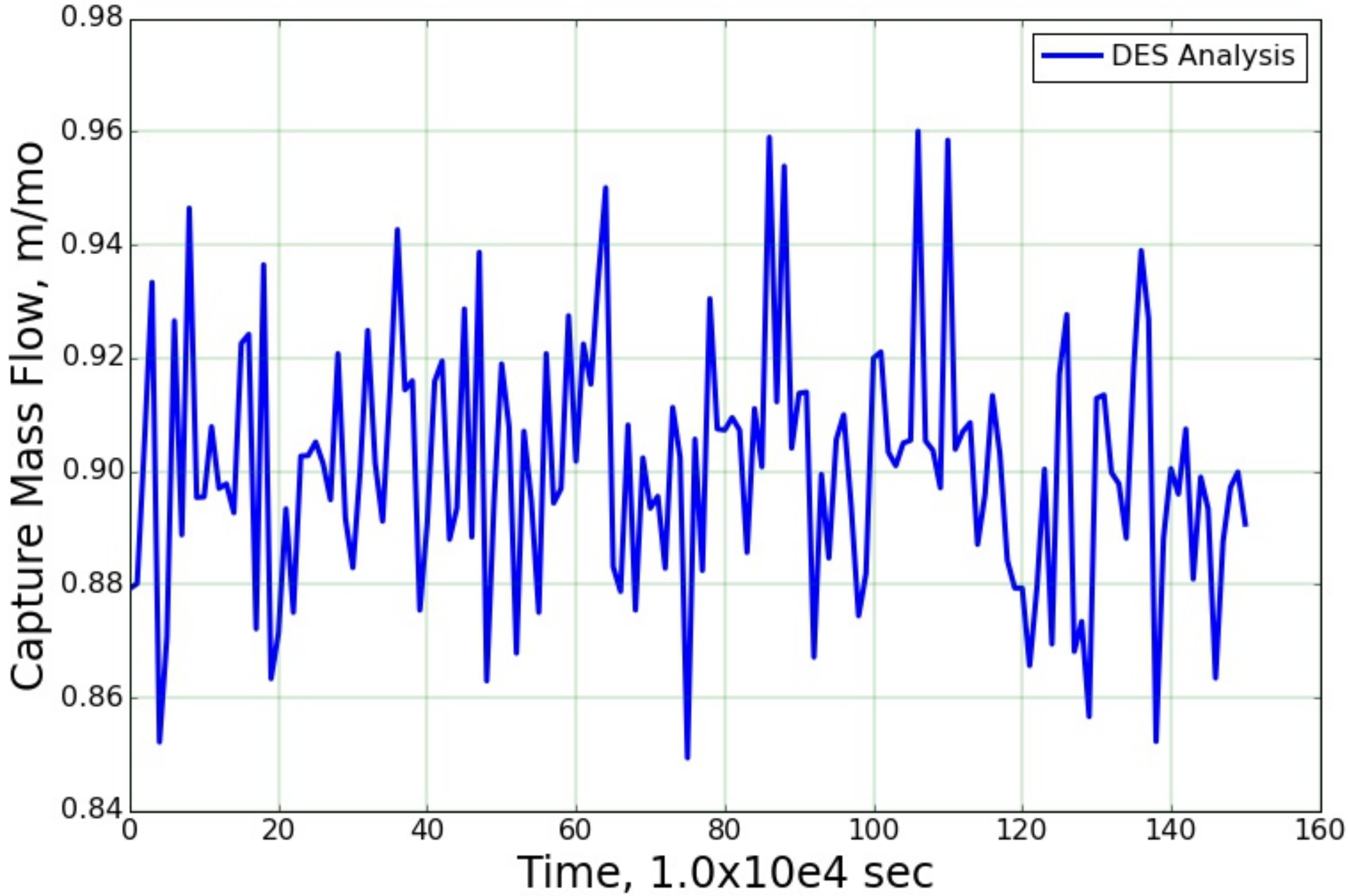
Time Variable	*Value*
Computational Time Step, Sec.	5.0×10^{-7}
CFD Data Sampling Rate, Sec	1.0×10^{-4} (1)
Per/Rev Time Span (4300 RPM), Sec.	1.395×10^{-2}
CFD Data Per/Rev Sampling Time Span, Sec (1)	1.4×10^{-2}
Total Number of Data Samples	*141*

(1)Equivalent to experimental sampling rate, 1.0×10^4 samples/sec

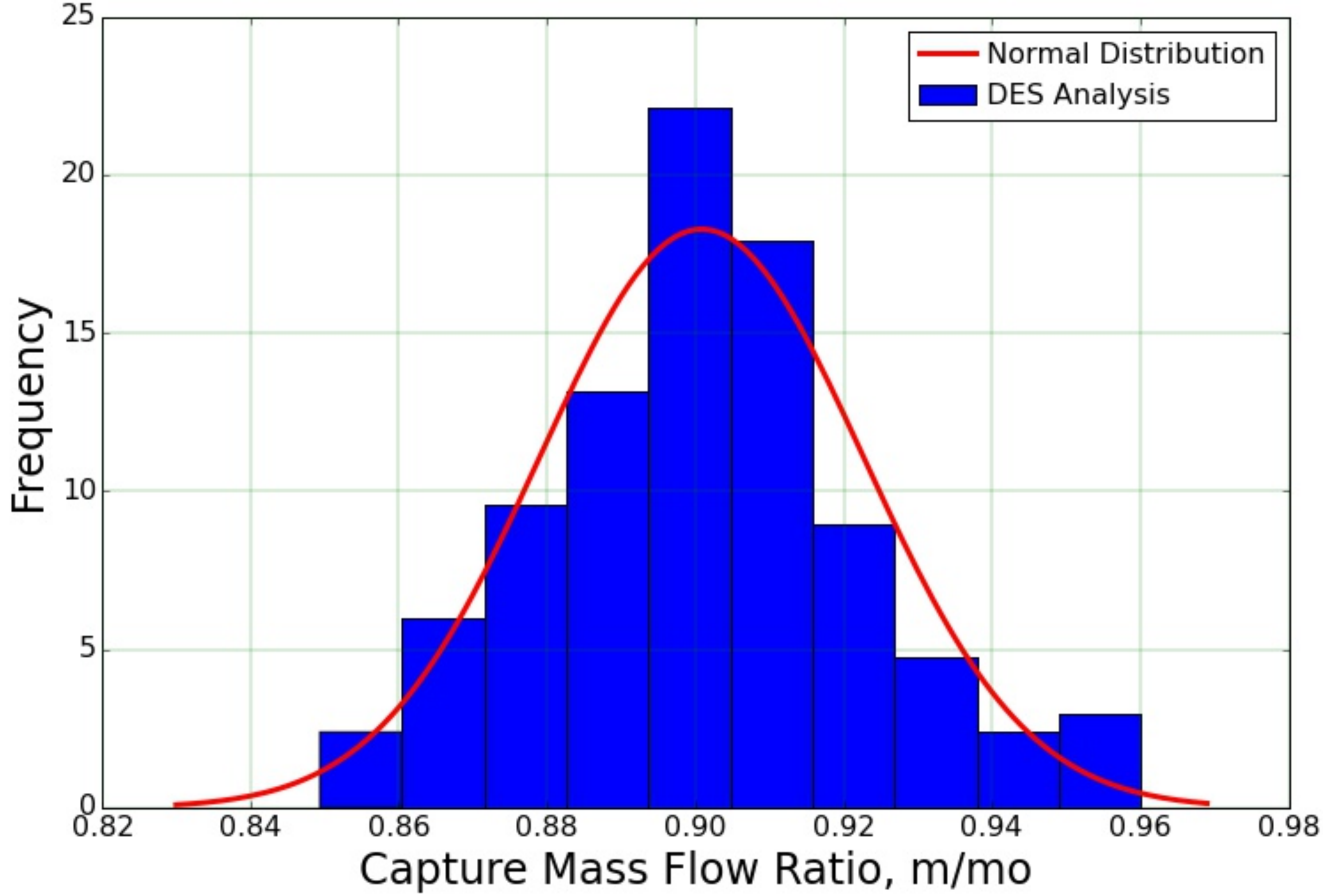
Boeing QEVC Low Boom Supersonic Inlet Design
Re = 6.275 x 10^5, Scale ≈ 1/43, M_0 = 1.560
Steady PFAIP Cane Curve



Boeing QEVC Low Boom Supersonic Inlet Design
Critical Operating Condition, $M_0 = 1.560$
Capture Mass Flow Ratio, m/m_0

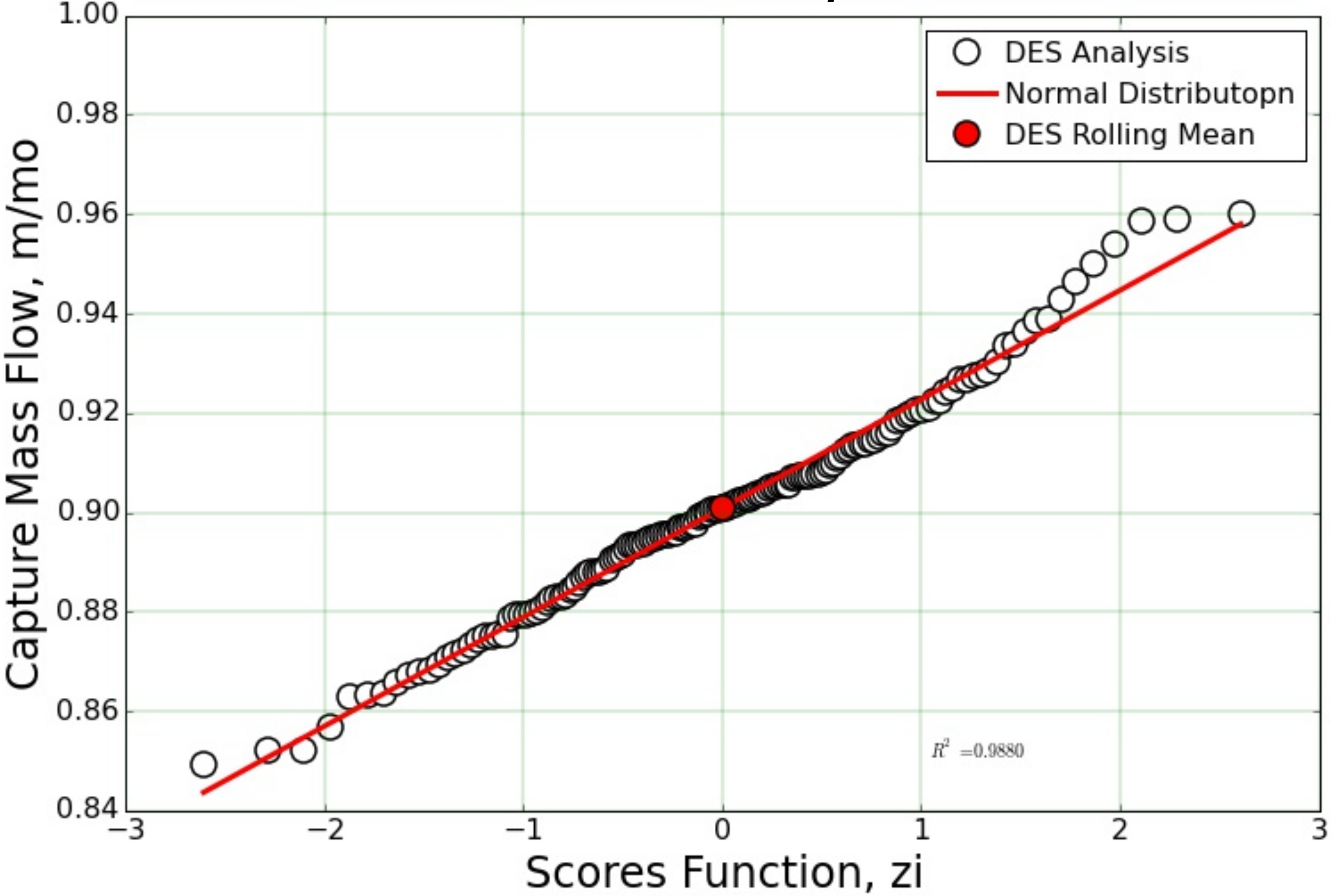


Capture Mass Flow m/mo Probability Distribution
Critical Operating Condition, M_0 = 1.560
m/m_0 Histogram Plot

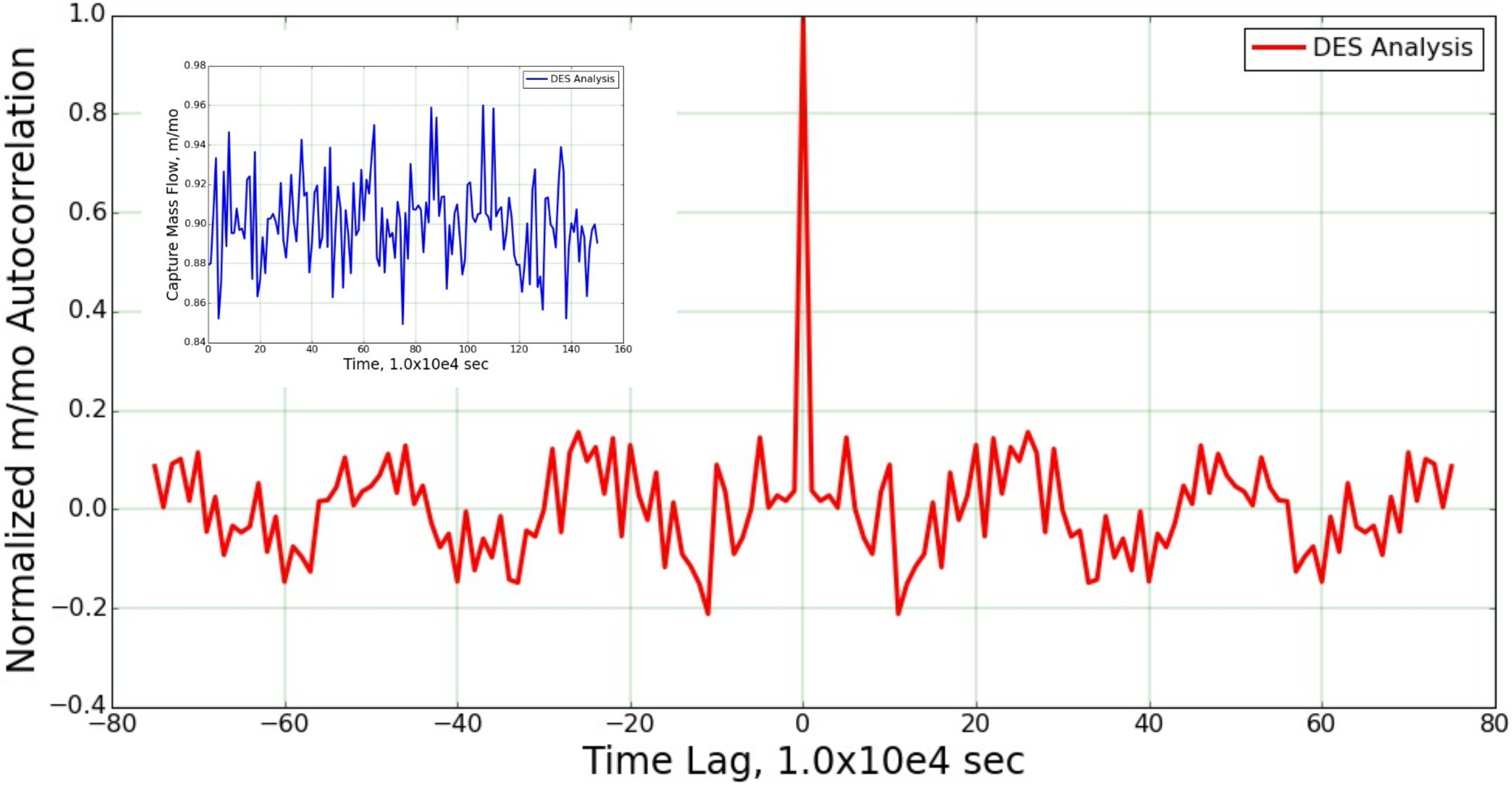


Frequency Occurrence Diagram

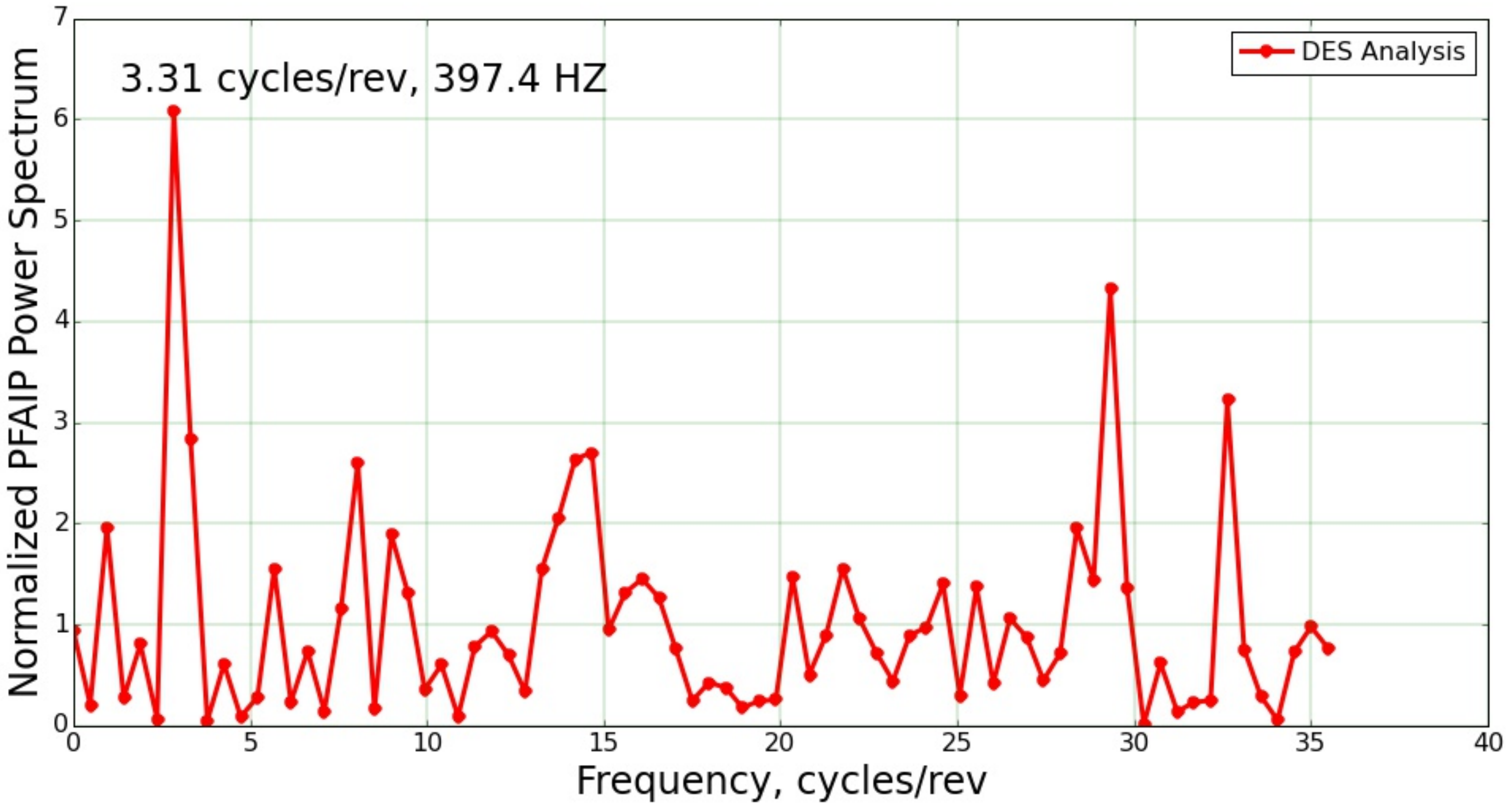
Capture Mass Flow m/mo Probability Distribution Critical Operating Condition, M_0 = 1.560 Normal Scores Plot, ρ = 0.9880



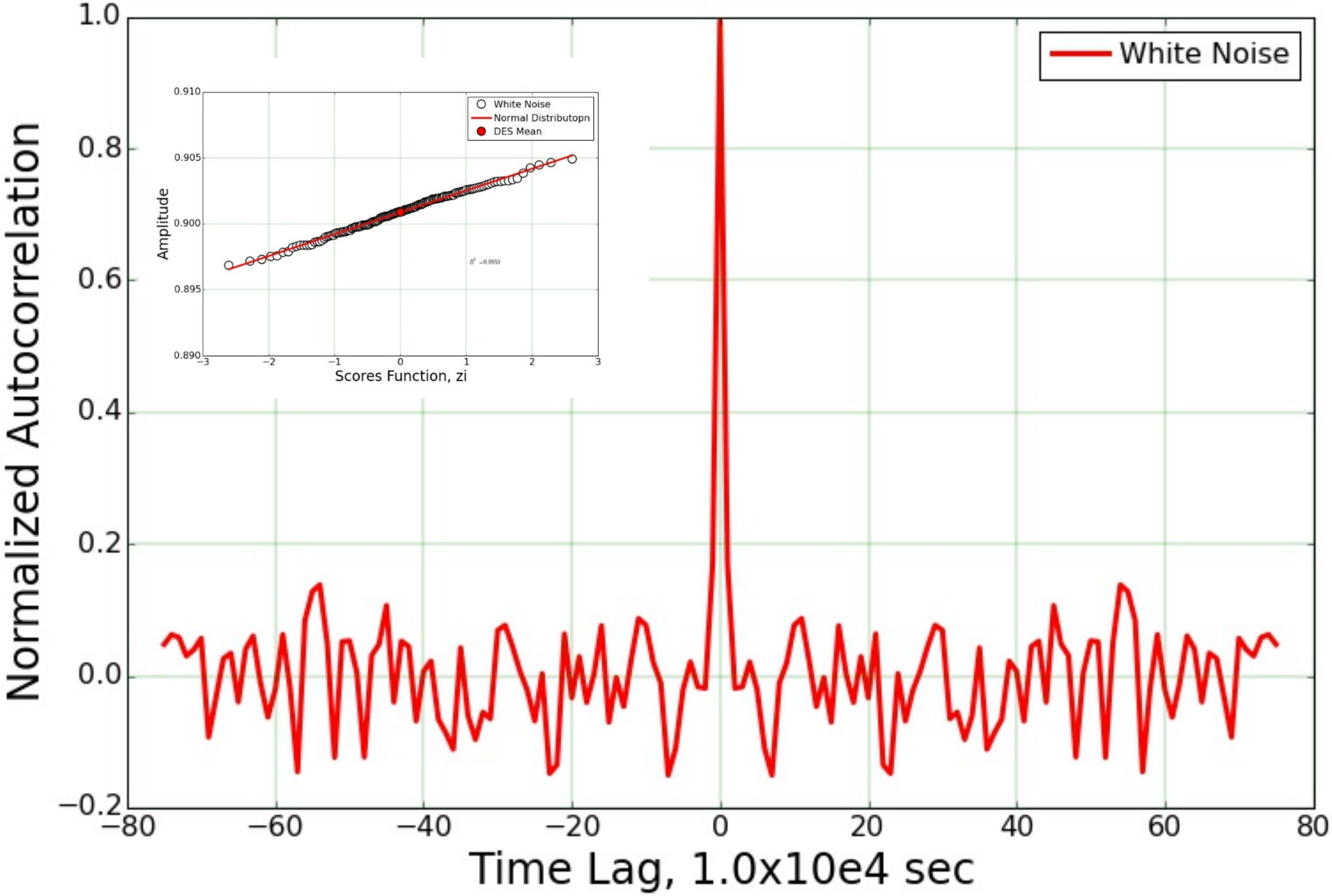
Boeing QEVC Low Boom Supersonic Inlet Design Critical Operating Condition, M_0 = 1.560 Normalized m/mo Autocorrelation



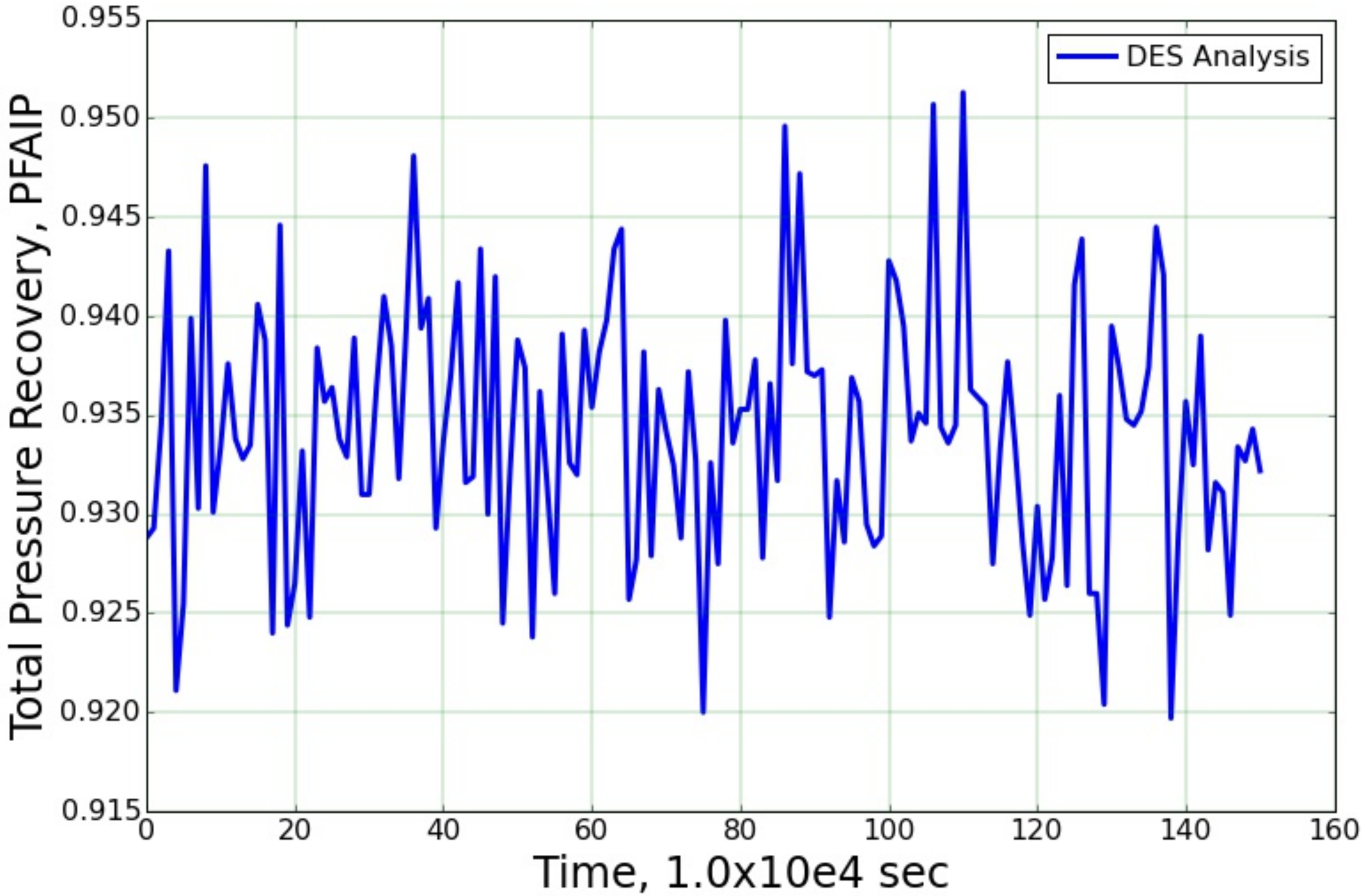
Boeing QEVC Low Boom Supersonic Inlet Design Critical Operating Condition, M_0 = 1.560 Normalized m/mo Power Spectrum



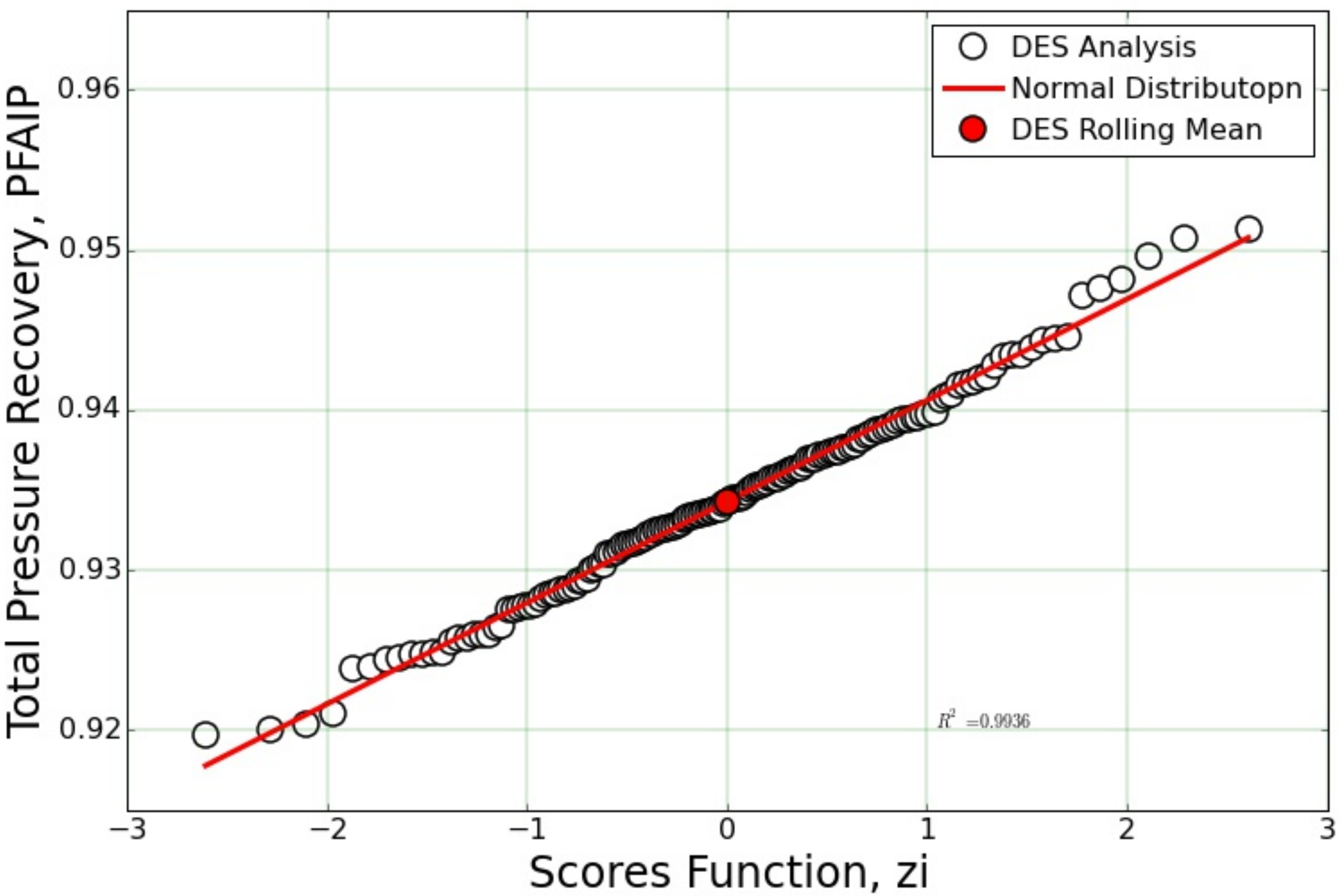
Boeing QEVC Low Boom Supersonic Inlet Design
Normalized Autocorrelation
White Noise



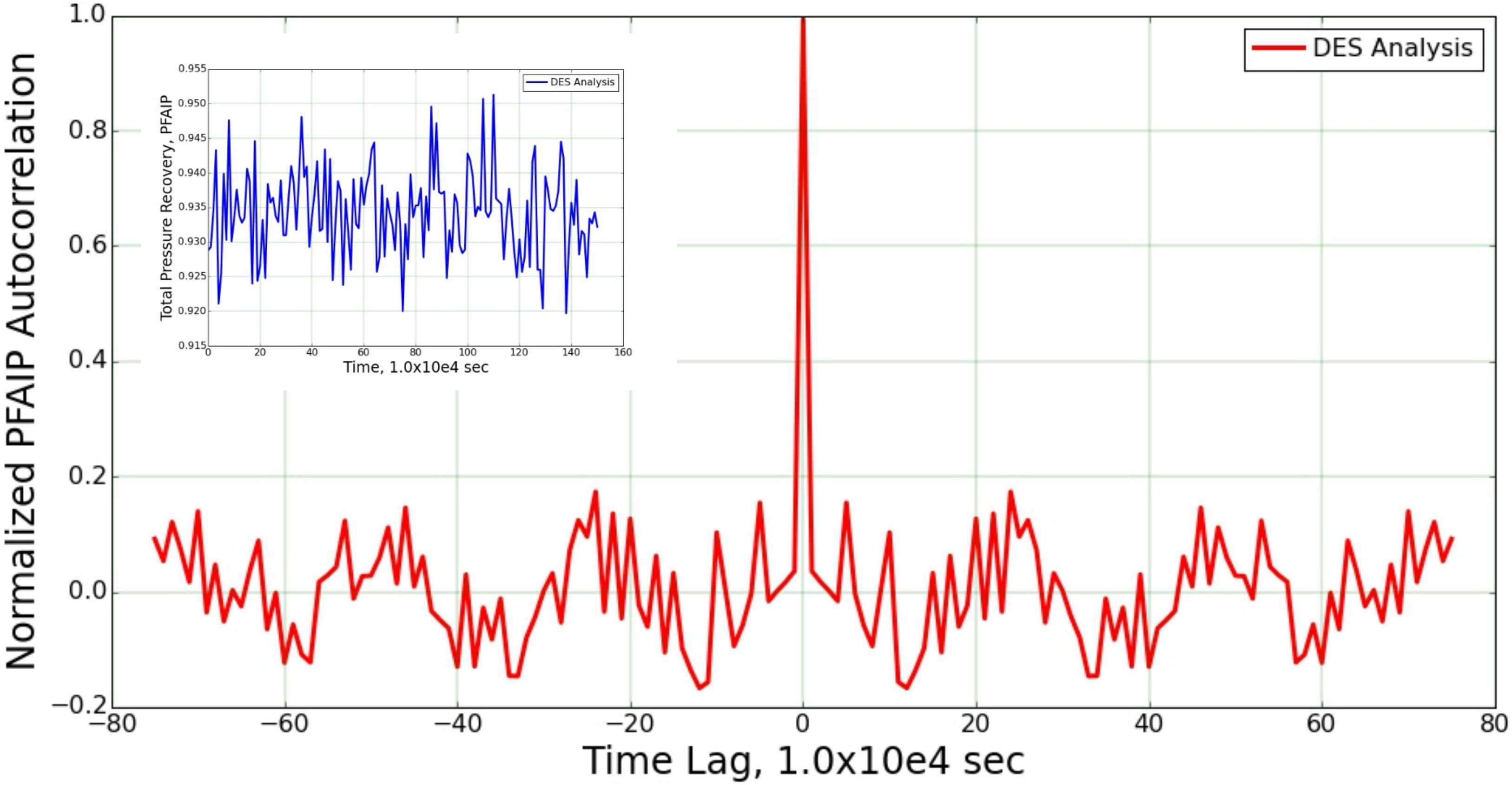
Boeing QEVC Low Boom Supersonic Inlet Design
Critical Operating Condition, M_0 = 1.560
Total Pressure Recovery, PFAIP



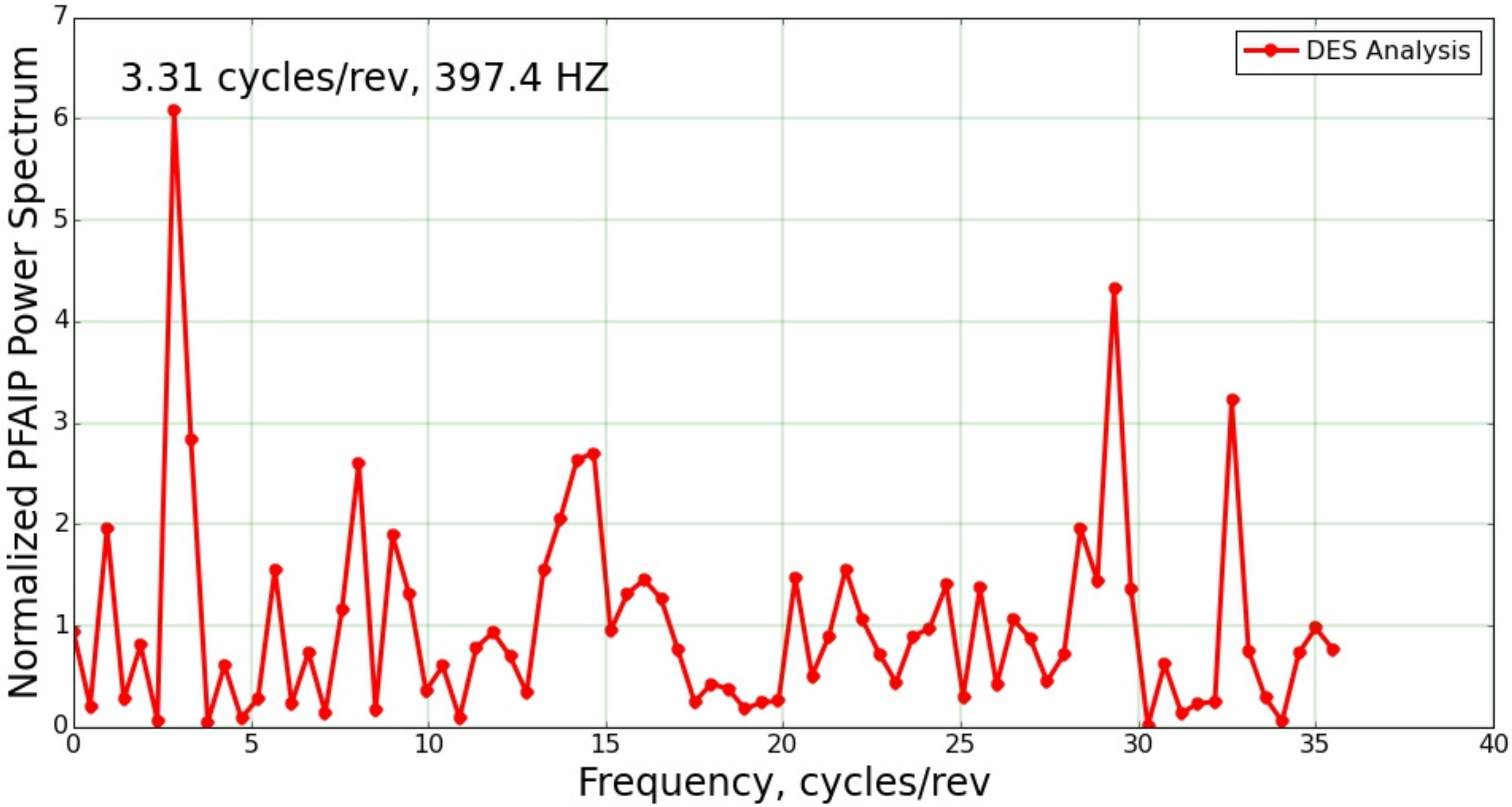
Total Pressure Recovery PFAIP Probability Distribution Critical Operating Condition, M_0 = 1.560 Normal Scores Plot, ρ = 0.9906



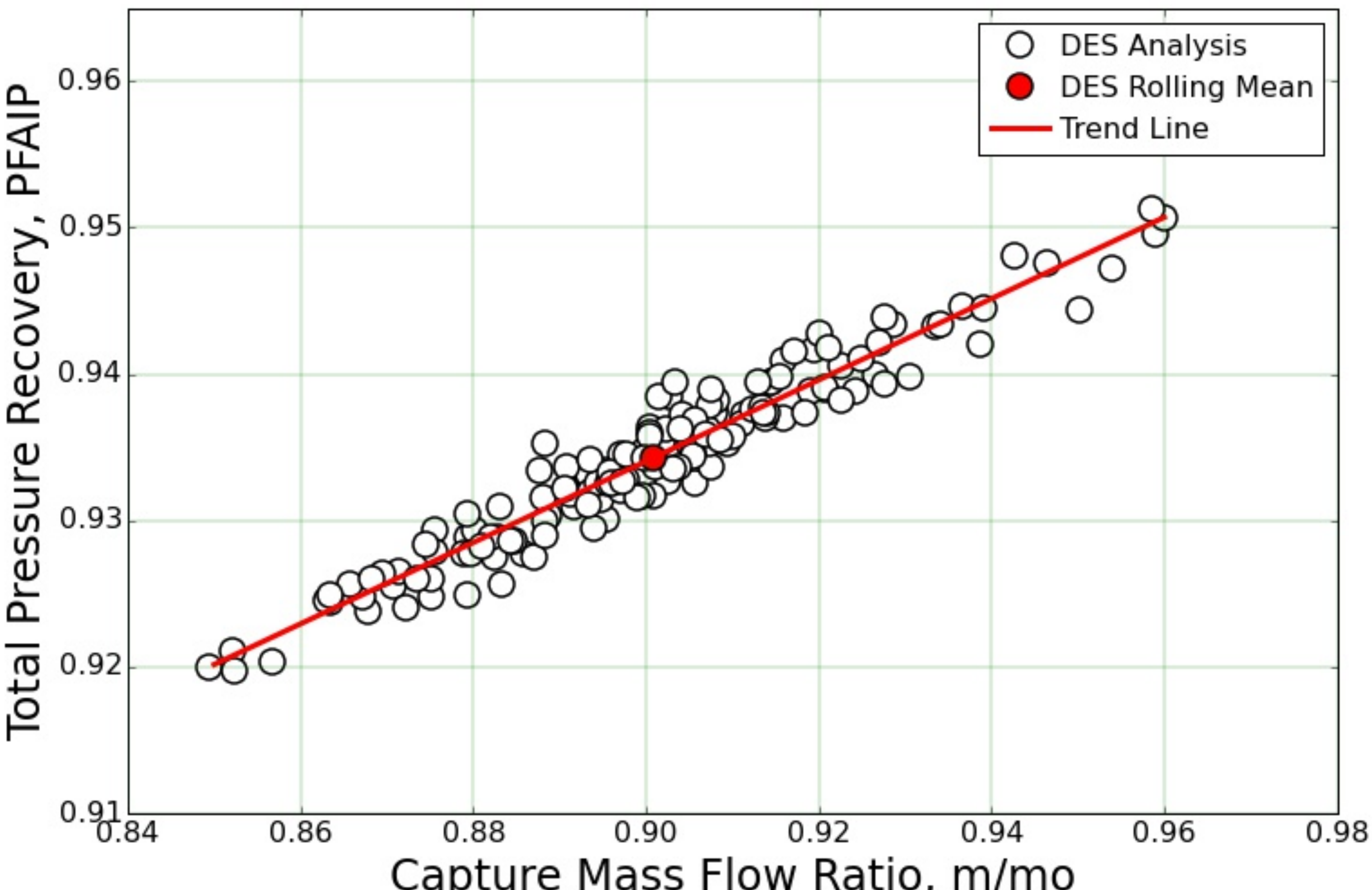
Boeing QEVC Low Boom Supersonic Inlet Design Critical Operating Condition, M_0 = 1.560 Normalized PFAIP Autocorrelation



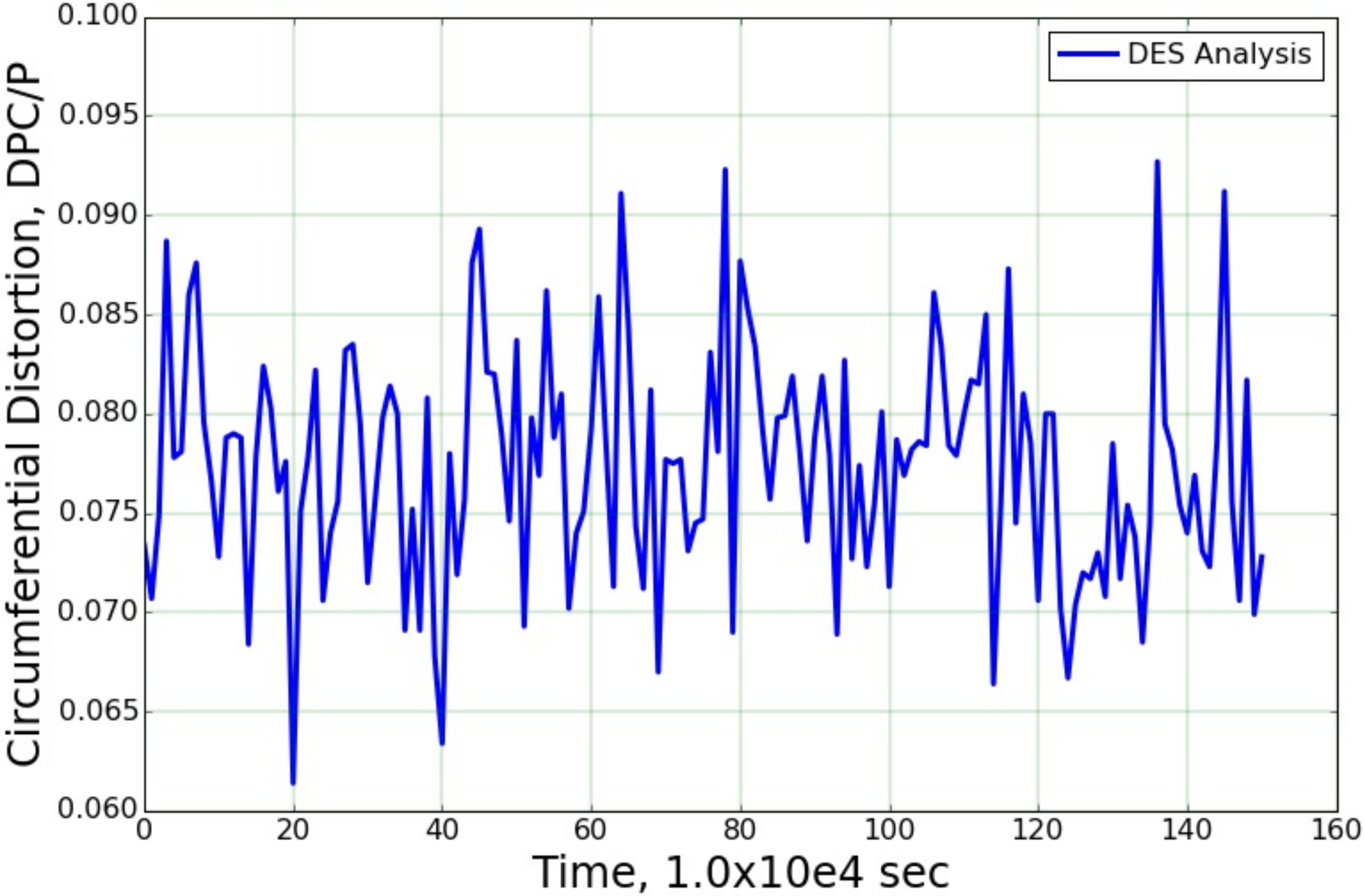
Boeing QEVC Low Boom Supersonic Inlet Design Critical Operating Condition, $M_0 = 1.560$ Normalized PFAIP Power Spectrum



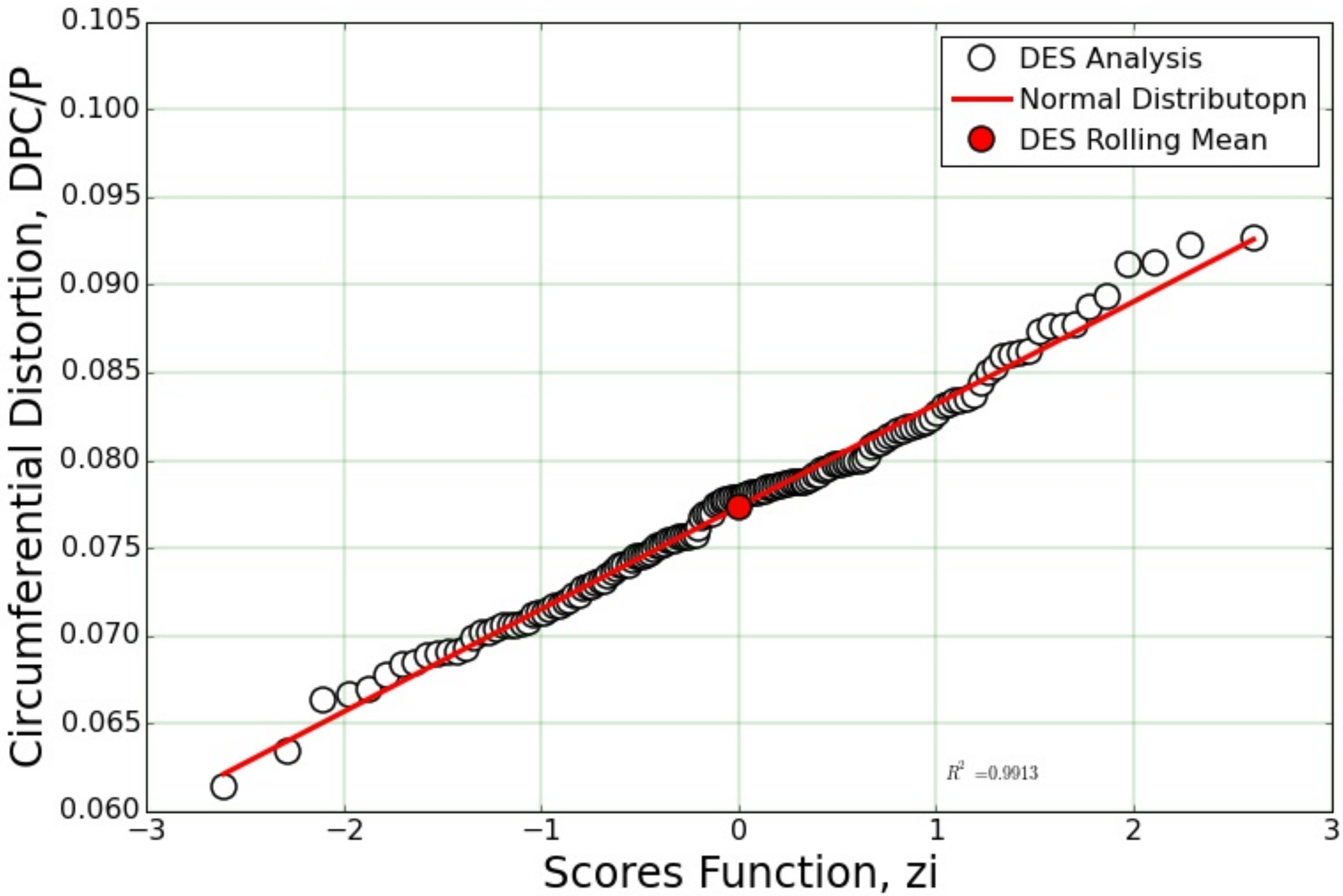
Boeing QEVC Low Boom Supersonic Inlet Design
Critical Inlet Operation, M_0 = 1.560
Scatter Plot, ρ = 0.984



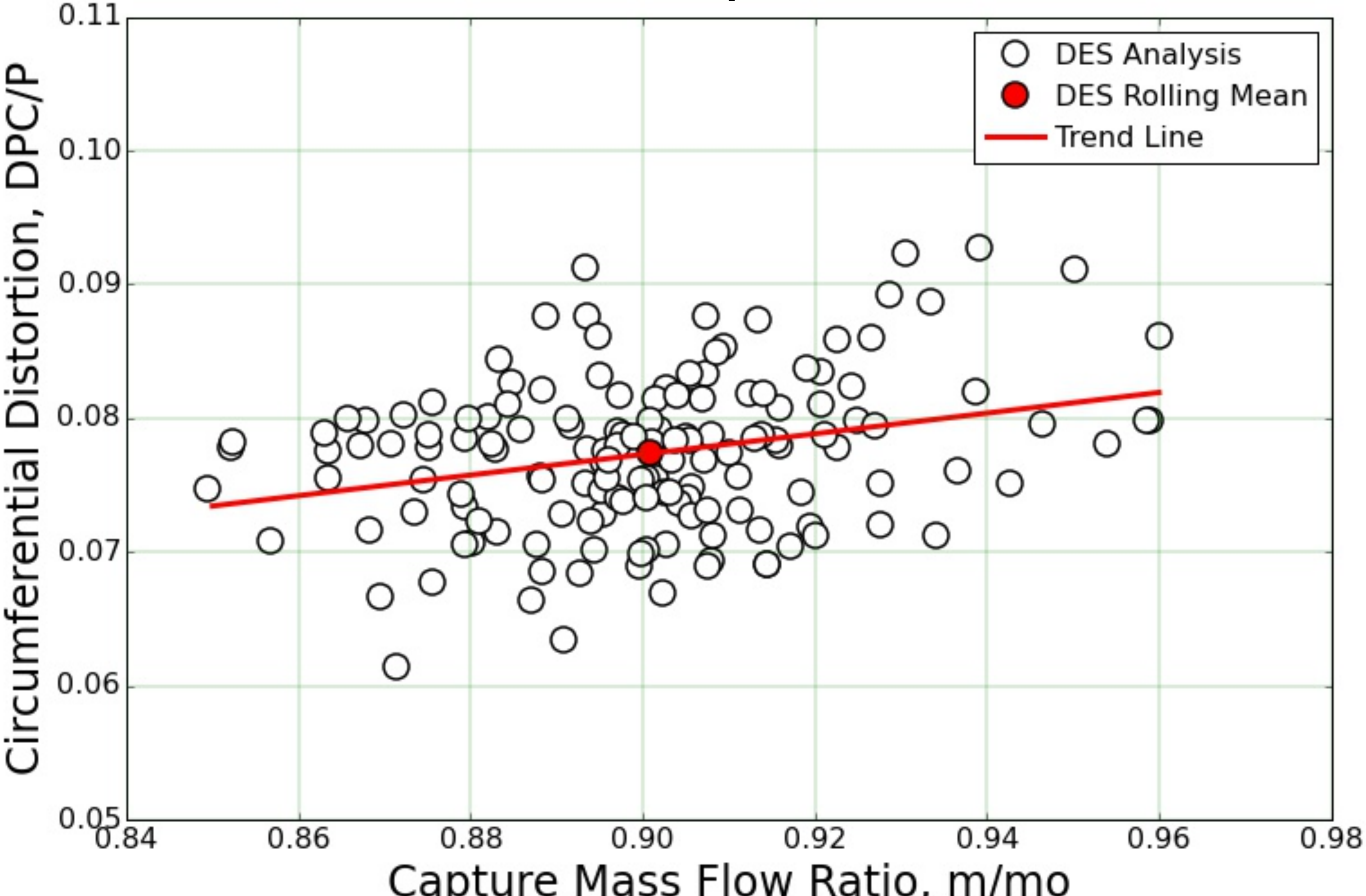
Boeing QEVC Low Boom Supersonic Inlet Design Critical Operating Condition, M_0 = 1.560 Total Pressure Recovery, DPC/P



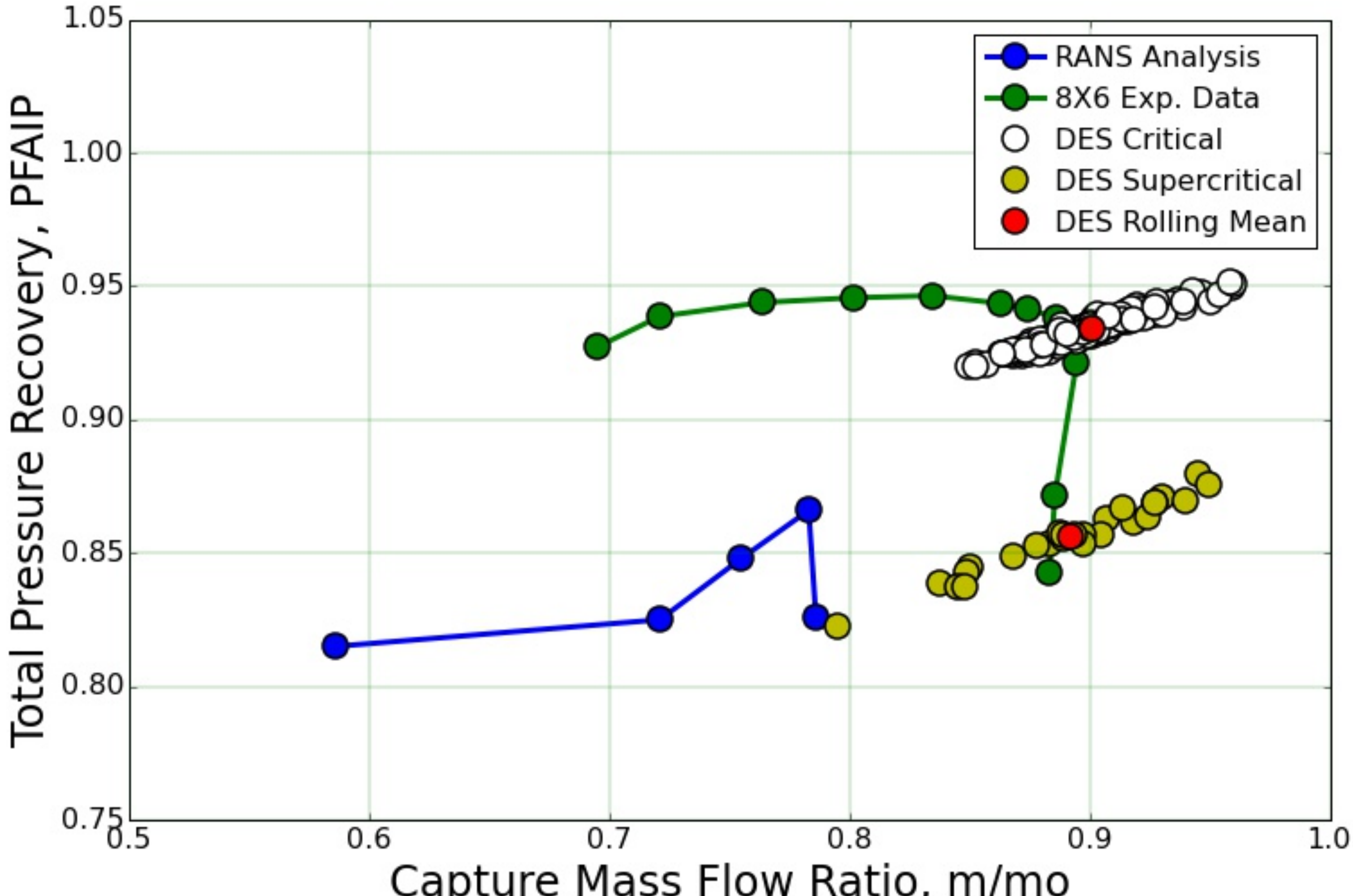
Circumferential Distortion DPC/P Probability Distribution
Critical Operating Condition, $M_0 = 1.560$
Normal Scores Plot, $\rho = 0.9913$



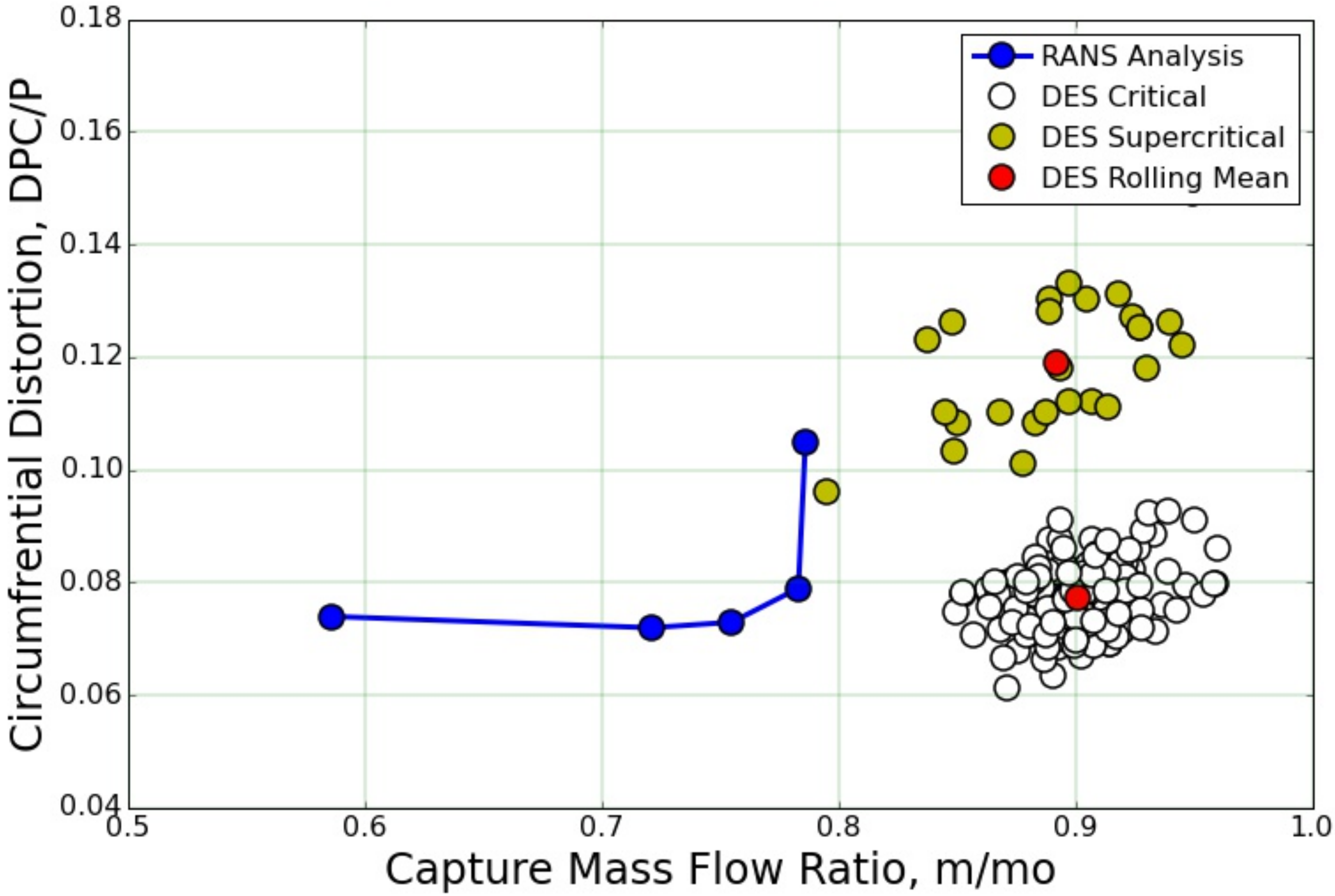
Boeing QEVC Low Boom Supersonic Inlet Design
Critical Inlet Operation, M_0 = 1.560
Scatter Plot, ρ = 0.289



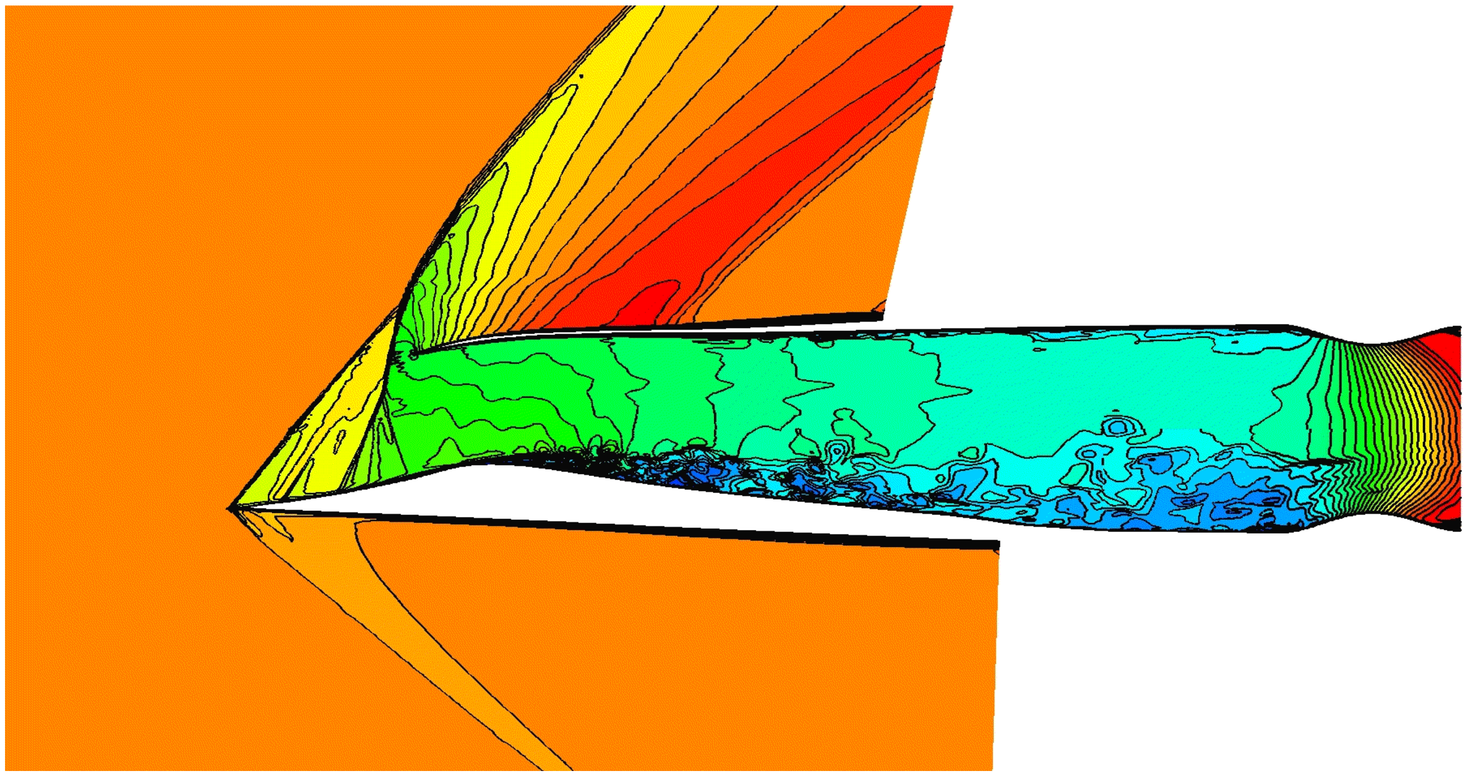
Boeing QEVC Low Boom Supersonic Inlet Design
Re = 6.275 x 10^5, Scale ≈ 1/43, M_0 = 1.560
Unsteady PFAIP Cane Curve



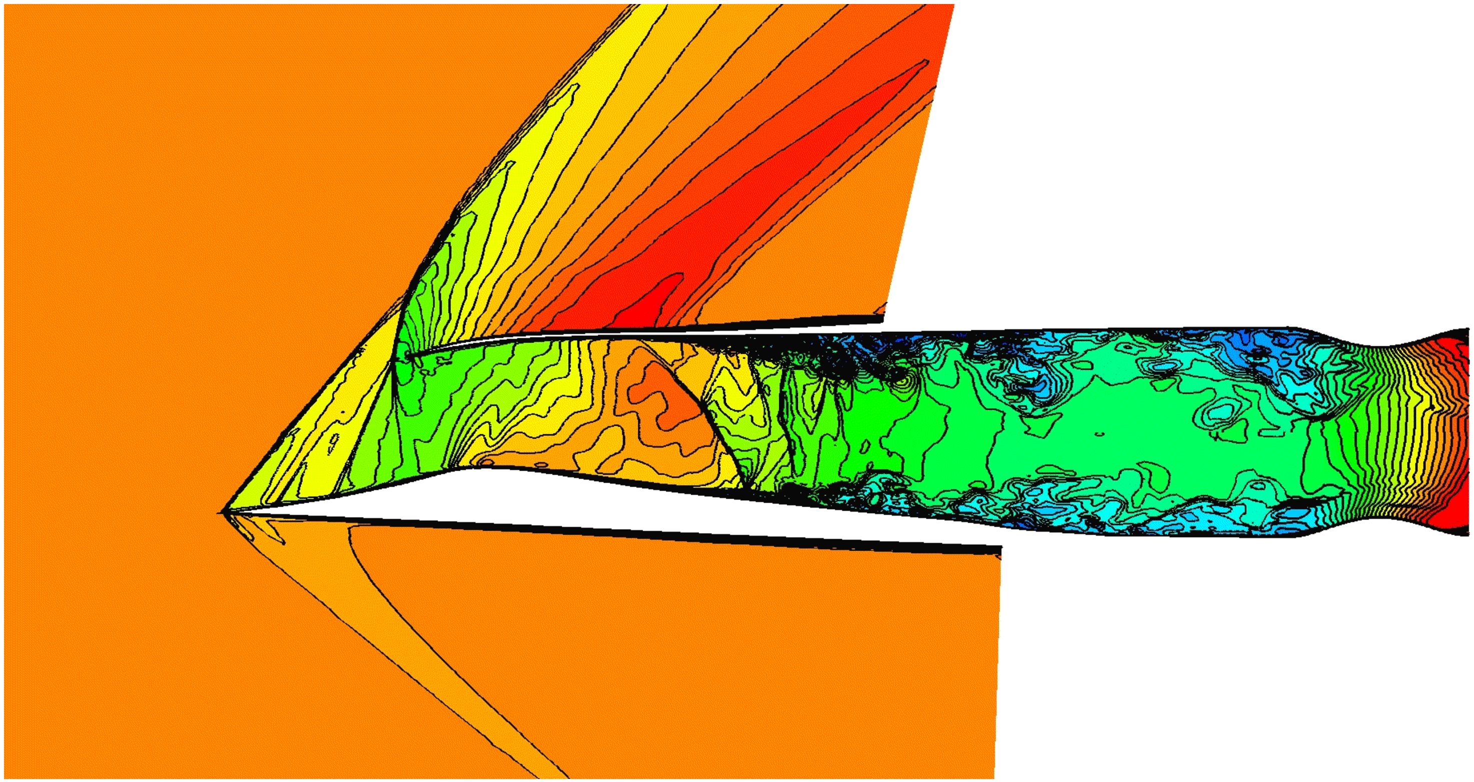
Boeing QEVC Low Boom Supersonic Inlet Design
$Re = 6.275 \times 10^5$, Scale $\approx$ 1/43, $M_0 = 1.560$
Unsteady DPC/P Cane Curve



Boeing QEVC Low Boom Supersonic Inlet Design
Critical Inlet Operating Condition, $M_0 = 1.560$
Streamwise Mach Number Contours



Boeing QEVC Low Boom Supersonic Inlet Design
Supercritical Operating Condition, M_0 = 1.560
Streamwise Mach Number Contours



Statistical Nature of Unsteady Inlet Flow General Conclusions

1. *DES solutions to unsteady inlet flows can give very good results, however, they are very costly, time consuming to analyze, and have many caveats associated the CFD analysis.*
2. *The unsteady flow associated with the QEVC Low Boom Supersonic Inlet Design was non-stationary, i.e. it has a mean flow that varies with time (commonly called a "rolling mean") at 3.31 cycles/rev or 397.4 HZ.*
3. *In spite of the fact that the unsteady flow exhibited a near perfect normal probability distribution, there existed a coherent structure in the time series.*
4. *There is a high correlation (ρ = 0.984) between unsteady capture mass flow ratio (m/mo) and unsteady total pressure recovery (PFAIP).*
5. *There is a low correlation (ρ = 0.289) between unsteady capture mass flow ratio (m/mo) and unsteady circumferential distortion (DPC/P).*
6. *In order to provide sufficient data for a complete time series analysis, data samples should cover a least four revolutions of the fan.*

Statistical Nature of Unsteady Inlet Flows Aerodynamic References

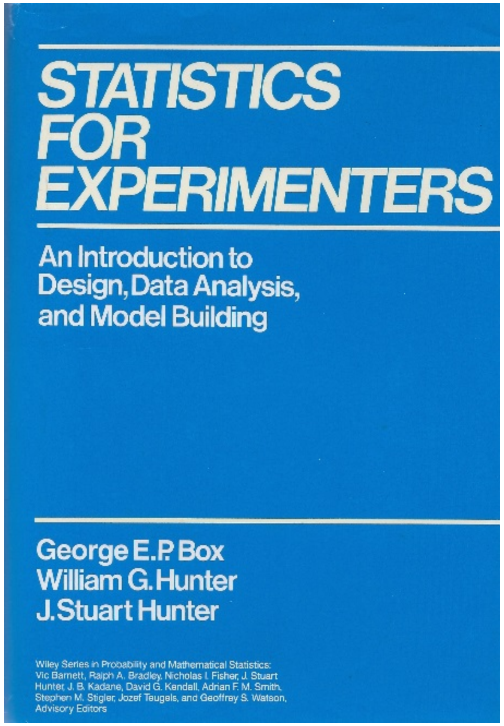
1. *Trefny, C J., Hirt, S. M., Anderson, B. H., Fink, L. E., and Magee, T. E., "Performance of a Supersonic Over-Wing Inlet with Application to a Low-Sonic-Boom Aircraft", AIAA Paper, 2014.*

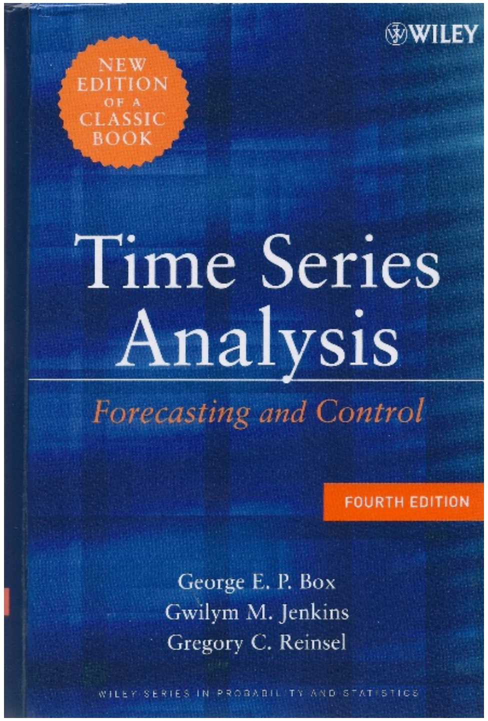
2. *Mace, J, Lakebrink, M, Mani, M, and Steeken, W: "Computational Simulation of Dynamic Total Pressure Distortion, AIAA Paper, 2014.*

Statistical Nature of Unsteady Inlet Flows Statistical References

3. *Box, G. E. P., Hunter, W. G., and Hunter, J. S., "Statistics for Experimenters," John Wiley, New York, 1978.*

4. *Box, E. P., Jenkins, G. M., and Reinsel, G. C.: "Time Series Analysis", John Wiley & Sons, 2008.*

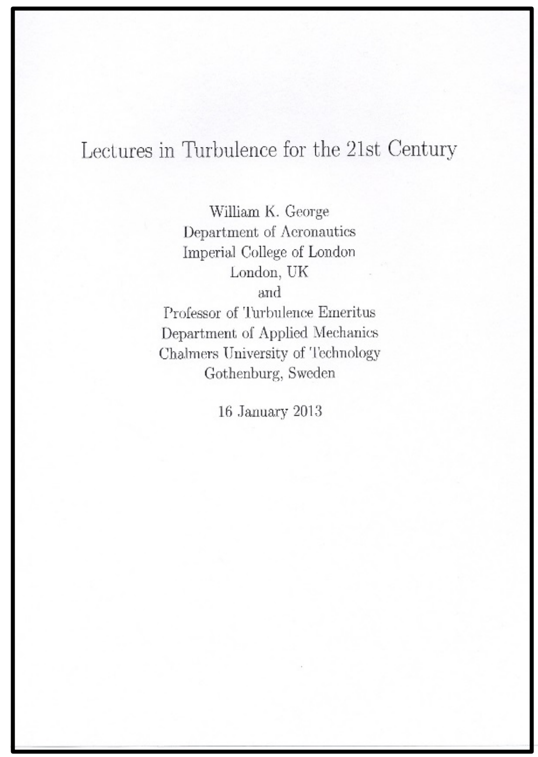




Statistical Nature of Unsteady Inlet Flows Turbulent Flow References

5. Monin, A. S., and Yaglom, A. M., "Statistical Fluid Mechanics", The MIT Press, Cambridge, Massachusetts, 1971

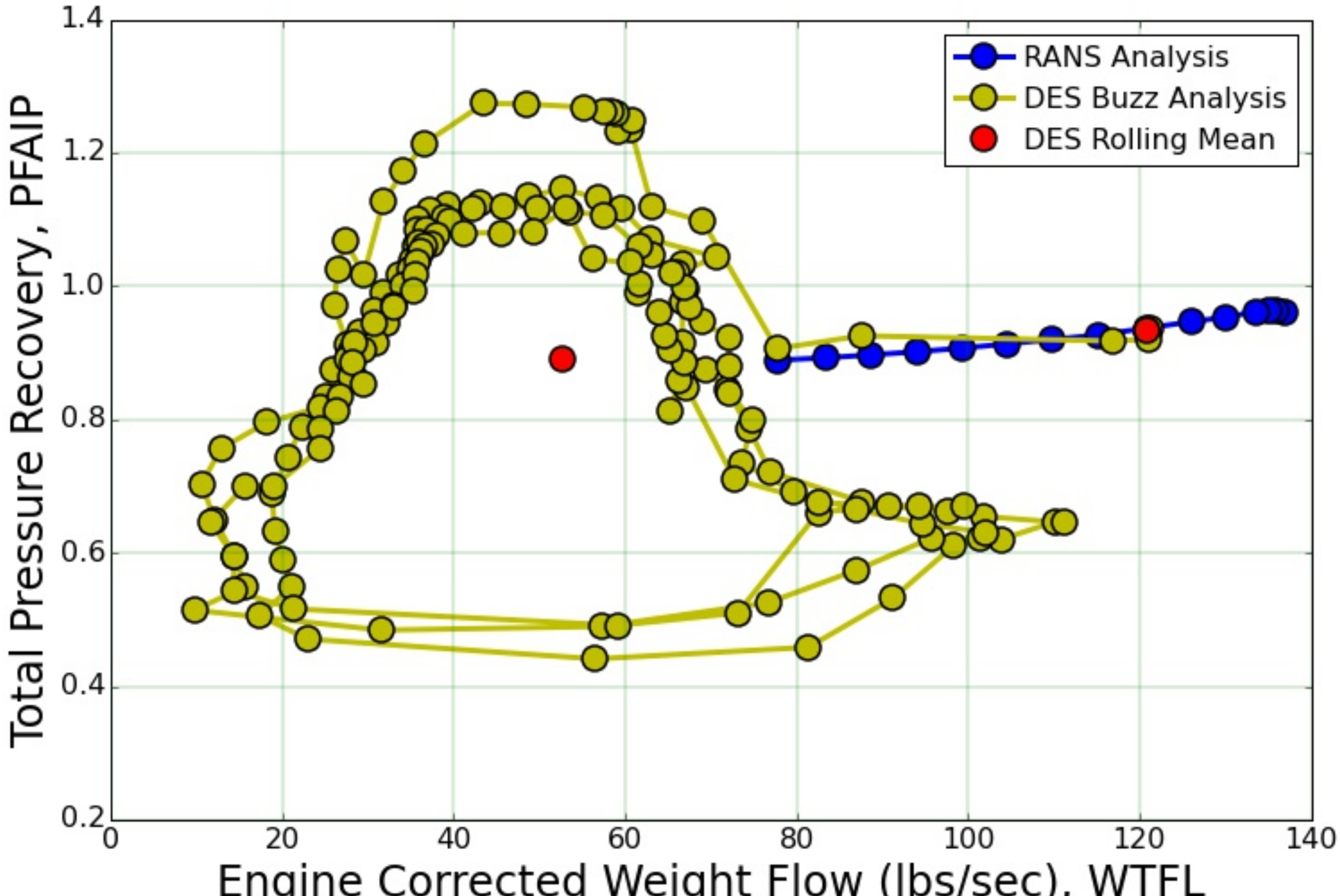
6. George*, W. K.: "*Lectures in Turbulence for the 21st Century", January, 2013.



The Statistical Nature of Inlet Buzz

Bernhard H. Anderson
NASA Glenn Research Center
Cleveland, Ohio, 44135

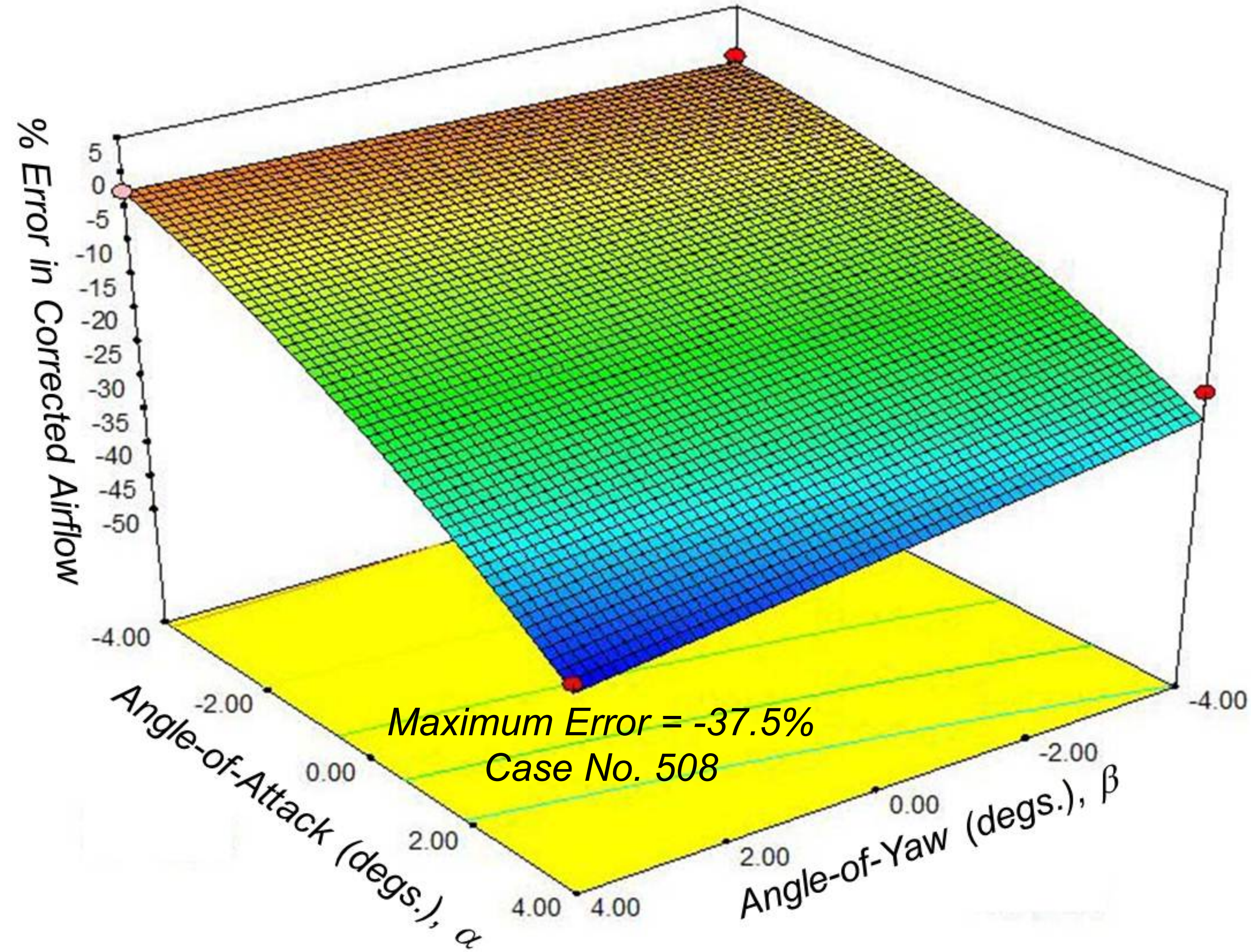
LMCO Low Boom Supersonic Inlet Design Unsteady PFAIP Cane Curve, M_0 = 1.70 Analysis of Inlet Buzz



The Role of Design-of-Experiments Methodology in Unsteady Inlet Flows

Bernhard H. Anderson
NASA Glenn Research Center
Cleveland, Ohio, 44135

Boeing Low Boom Supersonic Inlet Design
Engine Corrected Airflow Systemic Errors
Re = 8.068 x 10^6, Scale ≈ 1/3, M_0 = 1.80



The Role of Autocorrelations in Turbulent Flow Studies

Bernhard H. Anderson
NASA Glenn Research Center
Cleveland, Ohio, 44135

Auto-Correlations in Turbulent Flow Taylor Micro-Scale Region