

Fan Stage Broadband Noise Benchmarking Programme

Specification of Fundamental Test Case 3 (FC3)

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Test Case Coordinator

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Programme Website

The programme website is

<http://www.oai.org/aeroacoustics/FBNWorkshop>

Information on the programme organisation and all the test cases are available there.

Introduction

The purpose of this test case is to benchmark broadband noise calculation methods for the prediction of the far-field noise generated due to the ingestion of inhomogeneous turbulence into an idealized rotor.

Methods expected to be benchmarked for this test case include

- Analytic turbulence-plate interaction models
- CAA methods using stochastic source modelling
- Flow simulation methods such as LES or DNS

Submission of results using these or other relevant models will be welcomed.

Results submitted by contributors for this test case will initially be discussed and compared with the available experimental results during a Panel Session on Fan Broadband Noise Prediction to be held at the 21st AIAA/CEAS Aeroacoustics Conference in Dallas, Texas, USA, on 22-26 June 2015. Further details on the Panel Session will be available on the Programme Website.

The experimental data for FC3 is drawn from an experiment involving interaction of an open rotor with a planar boundary layer reported in Alexander *et al.* [1] and Wisda *et al.* [2]. Contributors seeking further general understanding of the flow and its sound field may also wish to consult the results from an earlier experiment reported by Alexander *et al.* [3], but should note that the rotor hub configuration and microphone locations were different for this test. Details of the origin of the 4D velocity correlation measurements defining the space-time correlation structure of turbulent boundary layer are given by Morton *et al.* [4].

The test section is 1.83m (between ceiling and roof) by 1.73m (between the port Kevlar wall and the starboard Lexan wall) and is 7.32m long. The rotor of diameter 457.2mm is mounted with its axis 248.9mm from the Lexan wall. The Lexan wall boundary layer is tripped approximately 4.76m upstream of the rotor resulting in the growth of a two-dimensional boundary layer of thickness around 101mm at the location of the rotor plane. The rotor and boundary layer arrangement are shown schematically on Figure 1(b). The background turbulence level, outside the wall boundary layers, is below 0.03%.

Rotor Geometry

The rotor has 10 identical (to within manufacturing tolerance) blades of 57.2mm chord at all radii. The tip diameter is 457.2mm. The hub diameter is 127.0mm. The tip gap to the Lexan wall is 20.3mm. The blades have square tips and no skew, sweep or lean. The blade pitch angle (stagger angle) varies non-linearly with radius from 55.6° at the root to 21.2° at the tip. The blade sections have a maximum thickness varying from 9.7% of chord at the root to 8.4% of chord at the tip, occurring approximately at mid-chord. The blade sections are stacked around an axis defined at the mid-chord of each section. The stacking axis is at a constant axial and azimuthal position for each radial section (i.e. no sweep or lean). The rotor blades and assembly are illustrated on Figure 2.

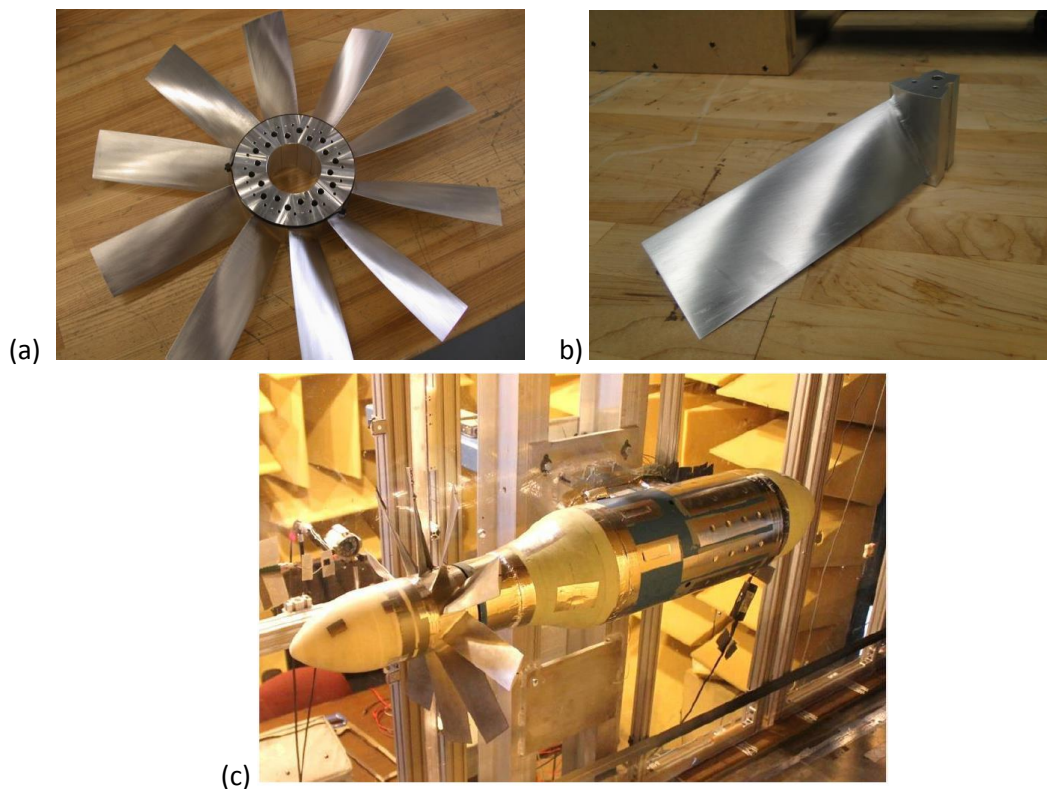


Figure 2 : The Rotor Blade Assembly

The rotor centerbody is axisymmetric and is supported by a pylon from the Lexan wall. The centerbody flares out downstream of the rotor to accommodate the downstream motor housing.

A full CAD file definition of the rotor geometry, including the centerbody and strut, can be requested from the test case coordinator.

Overall Test Section Aerodynamic Conditions

The flow velocity, U_∞ , in the test section is varied between 10m/s and 30m/s. The mean flow should be taken to be uniform over the test section, except for the wall boundary layers, with zero lateral and spanwise components.

Aerodynamic conditions of the test section flow should be set using

- Static density 1.08kg/m³
- Static sound speed 350m/s

The rotation speed of the rotor, Ω , varies between 2500 and 4500 RPM.

The flow velocity and rotor speed together define the advance ratio, J , defined by

$$J = \frac{U_\infty}{nD}$$

where $n = \Omega/60$ is the rotor speed in revs per second and D is the rotor diameter in metres.

The specific flow velocities and rotor speed for the test case computations are detailed in Table 1 below.

| Case | U_∞ (m/s) | Blade RPM | J |
|------|------------------|-----------|------|
| A | 30 | 2734 | 1.44 |
| B | 20 | 2500 | 1.05 |
| C | 30 | 4500 | 0.87 |
| D | 10 | 2500 | 0.52 |

Table 1 : Test Case Operating Conditions

Incoming Boundary Layer

With the rotor system removed, the flow along the test wall closely approximates a fully developed zero pressure gradient turbulent boundary layer [4]. Detailed measurements of this flow were made for a free-stream velocity of 30m/s at a position 4.72-m aft of the trip (0.04-m upstream of the rotor disk) to reveal the full 3-component 4-dimensional space-time correlation function of the turbulence in the cross-flow plane. The correlation is a function of time delay, separation in the homogeneous spanwise direction, and two normal-to-wall coordinates. Example maps are shown in figure 3, revealing the dependence of the correlation of the flow with a fixed point at 60% of the boundary layer thickness as a function of time delay and wall normal location. The results in this figure represent less than 0.3% of the measurements. To make these tractable the complete data set is encapsulated as a MATLAB function that can be used to access and interpolate the results using a calling syntax that exactly matches the functional form of the correlation. This greatly simplifies the use of this as part of a prediction.

The MATLAB function and associated data file defining the boundary layer 4D space-time correlation can be requested from the test case coordinator. Two-point correlations for speeds other than 30m/s can be obtained from these data by scaling on free-stream velocity.

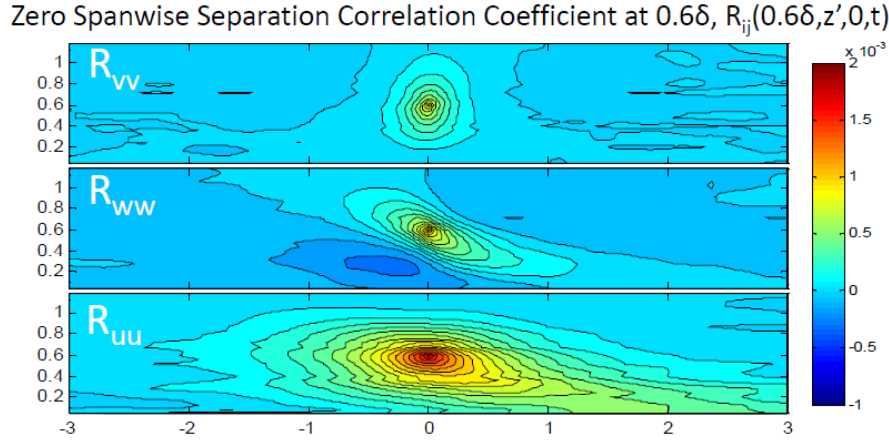


Figure 3 : Example Boundary Layer Correlation Coefficients

The incoming boundary layer was also measured in the presence of the rotor using a four-sensor hot-wire probe positioned 0.789m upstream of the rotor. The integral boundary layer characteristics are shown in Table 2. Due to error in the measurement, the boundary layer thickness for the 15m/s case has been interpolated from the results for the 10m/s and 20m/s cases.

A spreadsheet with the tabulated boundary layer profiles for each flow velocity may be requested from the test case coordinator.

| U_∞ , m/s | δ , mm | δ^* , mm | θ , mm |
|------------------|---------------|-----------------|---------------|
| 10 | 102.2 | 15.2 | 10.0 |
| 15 | 101.2 | 15.0 | 10.1 |
| 20 | 100.1 | 14.0 | 9.3 |
| 30 | 99.7 | 13.3 | 8.9 |

Table 2 : Boundary Layer Characteristics upstream of the rotor

Far-field Noise Measurement

The far-field noise due to the boundary layer interaction with the rotor is measured by a polar array of 8 microphones as shown on Figure 1. The exact positions of the microphones relative to the rotor are shown on Table 3. In the table, x is streamwise distance downstream of the disk plane, y is spanwise distance across the wall, z is the distance from the wall, and ϑ is the angle between the axis of rotation and the receiver as shown in Figure 1.

| Mic No. | x , m | y , m | z , m | θ , deg |
|---------|---------|---------|---------|----------------|
| 1 | 0.006 | -0.165 | 3.588 | 90.1 |
| 2 | -0.730 | -0.121 | 3.378 | 76.9 |
| 3 | -1.251 | -0.127 | 2.959 | 65.2 |
| 4 | -1.715 | -0.121 | 2.502 | 52.7 |
| 5 | -2.162 | 0.119 | 0.803 | 14.4 |
| 6 | -2.108 | -0.127 | 1.416 | 29.0 |
| 7 | 2.102 | 0.127 | 1.429 | 150.7 |
| 8 | 2.731 | -0.133 | 0.803 | 168.5 |

Table 3 : Microphone Positions

Rotor Frame Flow Measurements

Upwash velocity fluctuations (normal to chord) in the rotor frame of reference were measured using crossed hot-wire probes mounted on the blades 19mm in front of the leading edge of the rotor blade at a number of radial positions [1]. The measurements included a reference signal enabling the instantaneous position of the rotor corresponding to each velocity sample to be determined. Measurements were made for a large range of conditions including computational test cases B and D of Table 1. Four probes were on a leading blade at 98.5%, 95%, 90% and 80% of the blade radius, and an immediately succeeding blade had probes at 98.5% and 90% blade radius, figure 4.

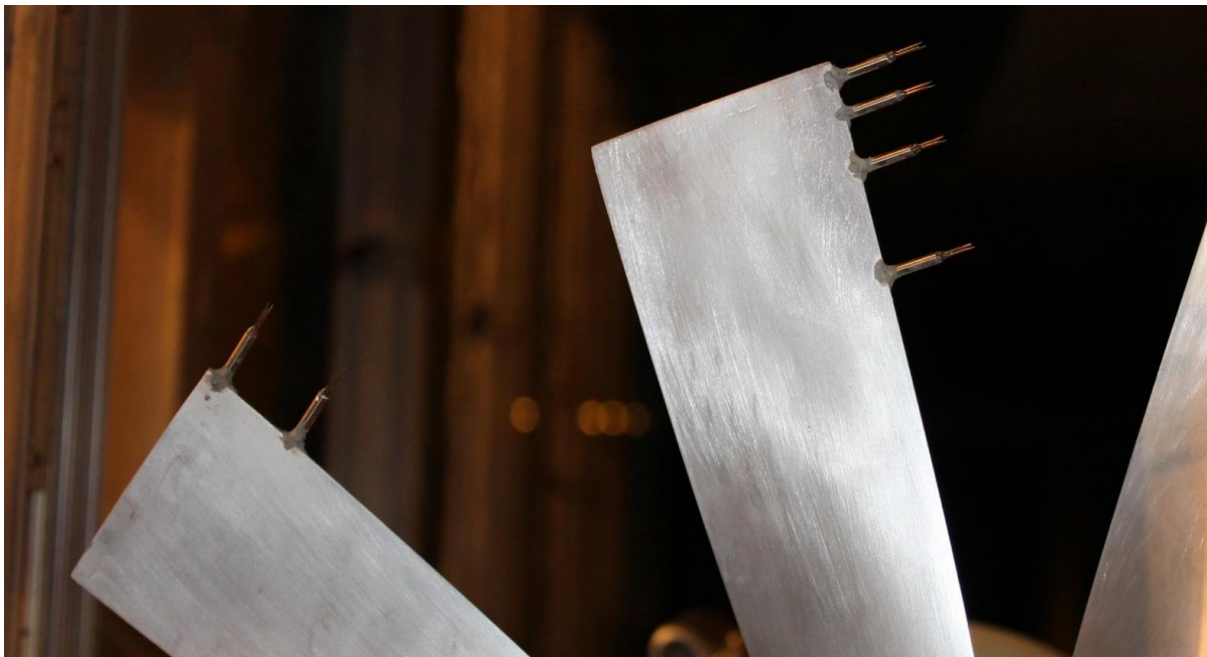


Figure 4 : Blade-mounted cross-wire probes. Blade rotation is clockwise as seen from this perspective.

The probes were used to measure the mean square upwash velocity as a function of radius (from 80% to 98.5%) and azimuth angle, as well as the coherence spectrum between upwash velocity fluctuations seen at different blade radii as well as between blades. Table 4 lists the probe combinations for which coherence measurements were made.

| | | Leading Blade | | | |
|----------------|--------|---------------|-----|-----|--------|
| | | 80% | 90% | 95% | 98.50% |
| Leading Blade | 95% | X | | | |
| | 98.50% | | | X | |
| Trailing blade | 90% | X | X | X | X |
| | 98.50% | | | X | |

Table 4: Location pairs for which upwash coherence spectra were measured

Measured Data Limitations

Acoustic measurements were limited to a range of frequencies between 300Hz and 10kHz. Wind tunnel background noise (which was subtracted from the final spectra) overwhelmed the measurements below 300Hz. The wind tunnel test section floor and ceiling and the Kevlar wall opposite the rotor are expected to be acoustically non-reflecting and the Lexan wall on which the rotor is mounted is expected to act as an acoustic mirror.

Upwash coherence spectra were determined for frequencies, normalized by the blade passing frequency, of between 0.05 and 10.

Required Data to be Submitted to the Test Case Coordinator

The following data must be submitted to the test case coordinator for the four operating conditions A to D in Table 1 :

- Single-sided sound pressure PSD spectra (SPL) in dB/Hz over the frequency range 300-10000 Hz (use a reference square pressure of $4.0 \times 10^{-10} \text{ Pa}^2$) for microphone 5 in Table 3. The data should be provided to the test case coordinator as a table of frequency versus SPL, either as a text file or in a spreadsheet. Data file names should be of the form 'FC3_ "Contributer Name" _SPL_OpX_Pos5.....', where X in the operating point (A to D).

Optional Data to be Submitted to the Test Case Coordinator

The following data may be optionally submitted to the test case coordinator for the four operating conditions A to D in Table 1 :

- Single-sided sound pressure PSD spectra (SPL) in dB/Hz over the frequency range 300-10000 Hz (use a reference square pressure of $4.0 \times 10^{-10} \text{ Pa}^2$) for microphones 1-4 and 6-8 in Table 3. The data should be provided to the test case coordinator as a table of frequency versus SPL, either as a text file or in a spreadsheet. Data file names should be of the form 'FC3_ "Contributer Name" _SPL_OpX_PosY.....', where X in the operating point (A to D) and Y the microphone position (1 to 4, 6 to 8).

The following data may be optionally be submitted to the test case coordinator for operating conditions B and D in Table 1

- Upwash coherence spectra γ^2 over the frequency range, normalized on blade passing frequency, of 0.05 to 10 for at least the 95% leading blade and 90% trailing blade probe combination highlighted in Table 4. The data should be provided to the test case coordinator as a table of frequency/BPF versus coherence, either as a text file or in a spreadsheet. Data file names should be of the form '*FC3_ "Contributer Name" _COH_OpX_PosYPosZ.....*', where X in the operating point (B or D) and Y the first probe position (e.g. L95 for 95% leading blade) and Z the second probe position (e.g. T90 for 90% trailing blade) of the probe combination.
- Mean square upwash velocity over the rotor disk between the 80% and 98% radius locations as a function of azimuthal angle. The data should be provided to the test case coordinator as a table of mean-square upwash velocity fluctuation, normalized on U_∞^2 versus radius and azimuthal angle in degrees. Azimuthal angle is measured in the direction of rotation from bottom dead center (i.e. closest to the boundary layer wall). Data file names should be of the form '*FC3_ "Contributer Name" _UPW_OpX.....*', where X in the operating point (B or D).

Acknowledgements

The support of Nathan Alexander and William Devenport, Virginia Tech, in setting up this test case for the fan broadband noise benchmarking programme is gratefully acknowledged.

References

1. Alexander, W.N., Devenport, W., Wisda, D., Morton, M.A. & Glegg, S.A.L., "Sound Radiated from a Rotor and it's Relation to Rotating Frame Measurements of Ingested Turbulence", 20th AIAA/CEAS Aeroacoustics Conference, AIAA 2014-2746, 2014
2. Wisda, D., Alexander, W.N., Devenport, W. & Glegg, S.A.L., "Boundary Layer Ingestion Noise and Turbulence Scale Analysis at High and Low Advance Ratios", 20th AIAA/CEAS Aeroacoustics Conference, AIAA 2014-2608, 2014
3. Alexander, W.N., Devenport, W., Morton, M.A. & Glegg, S.A.L., "Noise from a Rotor Ingesting a Planar Turbulent Boundary Layer", 19th AIAA/CEAS Aeroacoustics Conference, AIAA 2013-2285, 2013
4. Morton, M. A., Devenport, W. J. and Glegg, S., 2012, "Rotor Inflow Noise Caused by a Boundary Layer: Inflow Measurements and Noise Predictions", 18th AIAA/CEAS Aeroacoustics Conference, Colorado Springs, Colorado, June 4-6. AIAA 2012-2120