International Forum on Rotorcraft Multidisciplinary Technology
Seoul, Korea, Oct. 15-17, 2007

DLR’s S4 Rotor Code Validation With HART II Data: The Baseline Case

Berend G. van der Wall*, and Jianping Yin**

* DLR, Institute of Flight Systems, Braunschweig, Germany
(Tel : +49-531-295-2849; E-mail: berend.vanderwall@dlr.de)
** DLR, Institute of Aerodynamics and Flow Technology, Braunschweig, Germany
(Tel : +49-531-295-3313; E-mail: jianping.yin@dlr.de)

Abstract: S4 is the name of DLR’s high resolution rotor code for simulation of aerodynamics, dynamics, acoustics and flow field of isolated rotors like those being operated in the wind tunnel. In 2001, the HART II test was performed by DLR, ONERA, US Army AFDD, NASA Langley and DNW in the large low-speed facility (LLF) of the DNW. The test encompasses the Bo105 40% Mach scaled and dynamically scaled model rotor in descent flight condition creating a large amount of blade-vortex interaction (BVI) noise as the baseline (BL) case. Higher harmonic control (HHC) was applied at 3/rev with different phases for minimum noise radiation in a plane ranging ±2R in stream-wise and ±1.35R in lateral direction relative to the hub center. In addition, stereo particle image velocimetry (3C-PIV) was applied to trace the blade tip and secondary vortices from their origin downstream until leaving the rotor disk.

After several years of data analysis and analysis tools development like conditional averaging procedures for PIV [3], blade motion analysis [4], blade pressure and microphone data [5] the code validation phase has started. At DLR Institute of Flight Systems, since long an isolated rotor code named S4 was used for simulation purposes to support wind tunnel testing as well as for prediction of new actuation concepts and their benefits on rotor vibration, noise and performance [6]. It is applied here to HART II data from the BL case.

In addition, in 2005 some hover data including very high resolution PIV were added within the HOTIS test [7]. The HART II data are available to the rotorcraft community within the framework of the International HART II Workshop [8].

2. TEST CONDITION AND MODEL DATA

The test condition is a 6deg descent flight at moderate speed that is known to generate a lot of BVI noise. Rotor geometry and operating condition are provided in Table 1. The reference blade was equipped with 17 pressure transducers at a radial section of r/R = 0.87 as illustrated in Figure 1.

The chord-wise integration of the pressure distribution allows computing the sectional air loads in terms of the normal force coefficient C_{nM} that can be directly compared to simulation code data. Also, the measured span-wise and azimuthal blade deflections can directly be compared to simulation results.

![Figure 1: Pressure sensor distribution, r/R = 0.87.](image)

Table 1: Rotor geometry and operating condition.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>radius R</td>
<td>2m</td>
</tr>
<tr>
<td>chord (rectangular) c/R</td>
<td>0.0605</td>
</tr>
<tr>
<td>main bolt location r/R</td>
<td>0.075</td>
</tr>
<tr>
<td>root cutout r_{rc}/R</td>
<td>0.2</td>
</tr>
<tr>
<td>radius of zero twist r_{tw}/R</td>
<td>0.75</td>
</tr>
<tr>
<td>airfoil</td>
<td>NACA 23012</td>
</tr>
<tr>
<td>tab width Δx/R</td>
<td>0.0025</td>
</tr>
<tr>
<td>number of blades N_b</td>
<td>4</td>
</tr>
<tr>
<td>pre-twist (linear) Θ_{pw}</td>
<td>-8deg</td>
</tr>
<tr>
<td>pre-cone β_p</td>
<td>2.5deg</td>
</tr>
<tr>
<td>pre-lag c_p</td>
<td>0deg</td>
</tr>
<tr>
<td>rotational frequency Ω</td>
<td>109rad/s</td>
</tr>
<tr>
<td>shaft angle α_s</td>
<td>5.3deg</td>
</tr>
<tr>
<td>tunnel interference Δα</td>
<td>-0.8deg</td>
</tr>
<tr>
<td>advance ratio μ = V cos α_s / (Ω R)</td>
<td>0.151</td>
</tr>
<tr>
<td>rotor loading C_p/σ</td>
<td>0.057</td>
</tr>
<tr>
<td>hub moments C_{Mw}, C_{My}</td>
<td>0.0</td>
</tr>
</tbody>
</table>

In addition, wake positions determined by PIV analysis are also compared to the basic Beddoes wake geometry implemented in the S4 code. Finally the comparison can also be made for noise radiation in terms of the noise carpet plots.

Keywords: HART II, wind tunnel testing, code validation, unsteady air loads, blade dynamics, rotor acoustics

1. INTRODUCTION

In 2001 the HART II test [1] was performed in the LLF of the DNW using a hingeless Bo105 40% Mach scaled and dynamically scaled model rotor in order to add all wake data to the comprehensive data base of HART I from 1994 [2]. The HART II data range from rotor balance forces and moments including rotor power, blade root pitch angles and blade pressure measurements allowing the computation of sectional air loads at a radial position of r/R = 0.87.

The blade motion was optically measured by means of stereo pattern recognition (SPR) of markers located at the bottom of the fuselage and all along the span of the rotor blades from r/R = 0.228 to 0.993 at 18 radial stations, allowing the computation of elastic flap, lead-lag and torsion along span and azimuth. Microphones below the rotor recorded the noise radiation in a plane ranging ±2R in stream-wise and ±1.35R in lateral direction relative to the hub center. In addition, stereo particle image velocimetry (3C-PIV) was applied to trace the blade tip and secondary vortices from their origin downstream until leaving the rotor disk.

After several years of data analysis and analysis tools development like conditional averaging procedures for PIV [3], blade motion analysis [4], blade pressure and microphone data [5] the code validation phase has started. At DLR Institute of Flight Systems, since long an isolated rotor code named S4 was used for simulation purposes to support wind tunnel testing as well as for prediction of new actuation concepts and their benefits on rotor vibration, noise and performance [6]. It is applied here to HART II data from the BL case.

In addition, in 2005 some hover data including very high resolution PIV were added within the HOTIS test [7]. The HART II data are available to the rotorcraft community within the framework of the International HART II Workshop [8].

Table 1: Rotor geometry and operating condition.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>radius R</td>
<td>2m</td>
</tr>
<tr>
<td>chord (rectangular) c/R</td>
<td>0.0605</td>
</tr>
<tr>
<td>main bolt location r/R</td>
<td>0.075</td>
</tr>
<tr>
<td>root cutout r_{rc}/R</td>
<td>0.2</td>
</tr>
<tr>
<td>radius of zero twist r_{tw}/R</td>
<td>0.75</td>
</tr>
<tr>
<td>airfoil</td>
<td>NACA 23012</td>
</tr>
<tr>
<td>tab width Δx/R</td>
<td>0.0025</td>
</tr>
<tr>
<td>number of blades N_b</td>
<td>4</td>
</tr>
<tr>
<td>pre-twist (linear) Θ_{pw}</td>
<td>-8deg</td>
</tr>
<tr>
<td>pre-cone β_p</td>
<td>2.5deg</td>
</tr>
<tr>
<td>pre-lag c_p</td>
<td>0deg</td>
</tr>
<tr>
<td>rotational frequency Ω</td>
<td>109rad/s</td>
</tr>
<tr>
<td>shaft angle α_s</td>
<td>5.3deg</td>
</tr>
<tr>
<td>tunnel interference Δα</td>
<td>-0.8deg</td>
</tr>
<tr>
<td>advance ratio μ = V cos α_s / (Ω R)</td>
<td>0.151</td>
</tr>
<tr>
<td>rotor loading C_p/σ</td>
<td>0.057</td>
</tr>
<tr>
<td>hub moments C_{Mw}, C_{My}</td>
<td>0.0</td>
</tr>
</tbody>
</table>

In addition, wake positions determined by PIV analysis are also compared to the basic Beddoes wake geometry implemented in the S4 code. Finally the comparison can also be made for noise radiation in terms of the noise carpet plots.

Keywords: HART II, wind tunnel testing, code validation, unsteady air loads, blade dynamics, rotor acoustics

1. INTRODUCTION

In 2001 the HART II test [1] was performed in the LLF of the DNW using a hingeless Bo105 40% Mach scaled and dynamically scaled model rotor in order to add all wake data to the comprehensive data base of HART I from 1994 [2]. The HART II data range from rotor balance forces and moments including rotor power, blade root pitch angles and blade pressure measurements allowing the computation of sectional air loads at a radial position of r/R = 0.87.

The blade motion was optically measured by means of stereo pattern recognition (SPR) of markers located at the bottom of the fuselage and all along the span of the rotor blades from r/R = 0.228 to 0.993 at 18 radial stations, allowing the computation of elastic flap, lead-lag and torsion along span and azimuth. Microphones below the rotor recorded the noise radiation in a plane ranging ±2R in stream-wise and ±1.35R in lateral direction relative to the hub center. In addition, stereo particle image velocimetry (3C-PIV) was applied to trace the blade tip and secondary vortices from their origin downstream until leaving the rotor disk.

After several years of data analysis and analysis tools development like conditional averaging procedures for PIV [3], blade motion analysis [4], blade pressure and microphone data [5] the code validation phase has started. At DLR Institute of Flight Systems, since long an isolated rotor code named S4 was used for simulation purposes to support wind tunnel testing as well as for prediction of new actuation concepts and their benefits on rotor vibration, noise and performance [6]. It is applied here to HART II data from the BL case.

In addition, in 2005 some hover data including very high resolution PIV were added within the HOTIS test [7]. The HART II data are available to the rotorcraft community within the framework of the International HART II Workshop [8].

2. TEST CONDITION AND MODEL DATA

The test condition is a 6deg descent flight at moderate speed that is known to generate a lot of BVI noise. Rotor geometry and operating condition are provided in Table 1. The reference blade was equipped with 17 pressure transducers at a radial section of r/R = 0.87 as illustrated in Figure 1.

The chord-wise integration of the pressure distribution allows computing the sectional air loads in terms of the normal force coefficient C_{nM} that can be directly compared to simulation code data. Also, the measured span-wise and azimuthal blade deflections can directly be compared to simulation results.

![Figure 1: Pressure sensor distribution, r/R = 0.87.](image)

Table 1: Rotor geometry and operating condition.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>radius R</td>
<td>2m</td>
</tr>
<tr>
<td>chord (rectangular) c/R</td>
<td>0.0605</td>
</tr>
<tr>
<td>main bolt location r/R</td>
<td>0.075</td>
</tr>
<tr>
<td>root cutout r_{rc}/R</td>
<td>0.2</td>
</tr>
<tr>
<td>radius of zero twist r_{tw}/R</td>
<td>0.75</td>
</tr>
<tr>
<td>airfoil</td>
<td>NACA 23012</td>
</tr>
<tr>
<td>tab width Δx/R</td>
<td>0.0025</td>
</tr>
<tr>
<td>number of blades N_b</td>
<td>4</td>
</tr>
<tr>
<td>pre-twist (linear) Θ_{pw}</td>
<td>-8deg</td>
</tr>
<tr>
<td>pre-cone β_p</td>
<td>2.5deg</td>
</tr>
<tr>
<td>pre-lag c_p</td>
<td>0deg</td>
</tr>
<tr>
<td>rotational frequency Ω</td>
<td>109rad/s</td>
</tr>
<tr>
<td>shaft angle α_s</td>
<td>5.3deg</td>
</tr>
<tr>
<td>tunnel interference Δα</td>
<td>-0.8deg</td>
</tr>
<tr>
<td>advance ratio μ = V cos α_s / (Ω R)</td>
<td>0.151</td>
</tr>
<tr>
<td>rotor loading C_p/σ</td>
<td>0.057</td>
</tr>
<tr>
<td>hub moments C_{Mw}, C_{My}</td>
<td>0.0</td>
</tr>
</tbody>
</table>

In addition, wake positions determined by PIV analysis are also compared to the basic Beddoes wake geometry implemented in the S4 code. Finally the comparison can also be made for noise radiation in terms of the noise carpet plots.
3. S4 ROTOR CODE

3.1 Blade model and rotor trim

Elastic blades are represented within S4 as a sum of mode shapes in all degrees of freedom separately. Such, there are flap, lead-lag and torsion modes ideally separated from each other. Couplings from flap to torsion exist as much as any offset of the mass axis from the elastic axis creates a forcing moment, and from flap to lead-lag via Coriolis forces. The mode shapes are obtained from a finite element code that is run prior to any simulation. The mode shapes obtained for the HART II rotor are given in Figure 2. It must be noted that the boundary conditions at the main bolt are for flap and lead-lag a rigid connection, i.e. no deflection and no slope. In torsion, however, the condition at the bearing is a spring representing the control stiffness such that the mode already has a deflection right from the beginning that depends on the mode number.


during the simulation, the mode shapes are subjected to the generalized aerodynamic forces and generalized coupling forces from other modes like flap-torsion and flap-lag. The dynamic response problem is solved by means of time integration using Runge-Kutta of fourth order at a time step of 2deg in azimuth. An automatic trim algorithm varies the collective and cyclic control angles until the trim goal (here thrust and moments) is obtained with sufficient accuracy. The computation is made with account for tunnel interference.

3.2 Aerodynamic model

An unsteady two-dimensional semi-empirical aerodynamic model is used within S4 that is based on an analytical description of aerodynamic coefficients [9]. This covers positive and negative stall, compressibility and yaw effects. The unsteady flow conditions are separated with respect to their origin: one part is due to airfoil motion (all solid body motion, i.e. rotation, control, flexibility motion) and the other is due to the gust problem, i.e. containing wake velocities.

Different transfer functions are needed to account for the unsteady effects. The effective angle of attack is computed based on arbitrary motion theory with transfer functions related to both problems separately, i.e. in the incompressible case these functions are the Wagner functions for the body motion part, and the Küssner function for the gust part. Also, the unsteady motion has an effect on the stall incidence, but this is not effective here. In addition, the unsteady effects of periodic variations of the free-stream are accounted for [10].

3.3 Wake model

For computation of the induced velocities a modified version of Beddoes generalized wake geometry [11] is incorporated in the S4 code. These modifications are allowing for multiple trailers with different radial vortex release positions, which are computed based on the resulting blade bound circulation distribution. In the near wake, the entire array of trailed vortices is retained for the first 45deg of azimuth behind the trailing edge of the generating blade, then only the root, tip and eventually additional secondary trailed vortices are kept for the rest of the wake.

As an essential modification the higher harmonic rotor loading distribution is accounted for in as much as this causes additional vertical deflections of the wake system [12], which is mainly important at active control conditions with large loading variations. The core radius model is based on data from the HART II test and represents an average of core growth measured.

4. RESULTS

4.1 Blade loading

First, the steady part of the radial blade loading distribution in terms of blade circulation is compared to HART I and HART II data in Figure 3. It can be seen that HART II data are quite close to HART I data, i.e. the same thrust was obtained. Also, S4 loading is quite similar to HART I data, except for a higher loading right at the blade tip.

The dynamic loading in terms of $C_{m}M^2$ time history is
compared next in Figure 4. First, the fundamental 2/rev oscillation is nicely predicted, and also the BVI location and magnitude on the retreating side is perfectly matched. On the advancing side some discrepancies can be seen, but again the location of BVI as well as its magnitude appears to be quite acceptable.

![Figure 4: Section loading at r/R = 0.87.](image)

The BVI locations within the rotor disk can best be viewed by means of the high pass filtered leading edge pressure distribution of the experimental data, and be compared to the high pass filtered loading distribution of the simulation. This is allowed since the leading edge pressure fluctuation is the source of high frequency loading. It is also only meant for a qualitative comparison of BVI locations and its intensity. This comparison is done in Figure 5. Despite some differences in the radial and azimuthal interaction geometry the simulated BVI locations are quite well predicted.

![Figure 5: BVI locations in the rotor disk. Top: HART II leading edge pressure distribution, bottom: S4 loading.](image)

### 4.2 Blade tip deflection

The blade tip deflection was measured using SPR method for all four blades. Thus, the blade-to-blade variation can be investigated. This is shown in Figure 6, where the symbols mark the HART II data and the red line the S4 result, which is nicely reflecting the steady and 1/rev variation as well as the small higher harmonics on top of it. It must be noted that the measurement accuracy is within the line thickness and the airfoil thickness which is 0.726 of the scale. So in general there are very small deflections at all. However, it can be seen that all blades do have a different offset (meaning they carry a different mean lift), but the same dynamics.

![Figure 6: Blade tip deflection in flap.](image)

The other important deflection is the blade torsion since it is directly affecting the blade loading. This is shown in Figure 7 and compared to the S4 result. In torsion, the measurement accuracy is 0.5deg. With respect to this the S4 simulation is quite acceptable since it correctly represents the steady torsion and the 2/rev oscillation on top of it.

![Figure 7: Blade tip deflection in torsion.](image)

### 4.3 Noise radiation

The unsteady airloads on the rotor blades produced by S4 are used as input for a FWH-equation based code APSIM with thickness and loading terms only to analyse the noise radiation. For the incompressible flow considered in this study, quadrupole noise contribution is assumed to be negligible. The calculations, performed in the time domain, deliver a pressure time history at any desired observer location. This is Fourier analysed to arrive at the acoustic spectrum. A more detailed description of the approach is available in [13] and [14].

The noise radiation is the most critical part of code validation since it is extremely sensitive to any differences in BVI locations and the loading, especially time gradients of the loading at these. A comparison of BVI related loading and its time gradients on the advancing side between azimuth angle ranges of 40 and 65 deg. at r/R = 0.87 are given in Figure 8.

S4 results are available at 2deg time steps (star symbols),
while experimental data are at 0.176deg time steps and thus at a significantly higher resolution. Therefore, S4 results in its original resolution cannot correctly provide the signature around the peaks.

To circumvent this problem, the S4 data are interpolated using a local spline fit to a resolution of 0.25deg. This spline fit is using four consecutive data samples, fitting a polynomial of 3rd order to these, and analytically compute 7 additional points in between the two central points of the fit. This provides a smooth distribution with exactly the data of the 2deg resolution, interpolated to 0.25deg.

As can be seen the magnitude and signature of the experimental data are well simulated, although a phase difference of about 4deg in azimuth is existing, which represents about one chord length offset in wake vortex position.

![Figure 8: BVI loading on the advancing side, r/R = 0.87, high pass filtered. O: HART II data; *: S4 (2deg); Δ: S4, interpolated. Top: time history, bottom: time derivative.](image)

Next, the HART II data for the noise carpet (BVI mid-frequency noise level) is shown in Figure 9. There is a hot spot with just 114dB on the advancing side and a second one with just 112dB on the retreating side.

These are now compared to the S4 results, based on the non-linear interpolated loading data as just explained. The result of the acoustic post-processing by APSIM is given in Figure 10. The color scales may not be compared since they are different in these figures, but the dB level at the contour lines should be taken as reference. Also, the x scale is opposite in these graphs due to different sources.

However, the important parameter is the distribution of dB levels and the directivity of the noise. The general distribution, i.e. directivity, is predicted well, and the absolute dB levels at the peak intensities are correct on the retreating side (112dB), and on the advancing side (114dB). For this kind of comprehensive code this appears quite reasonable and it can be anticipated that only with free-wake modeling a better result can – but not must – be obtained.

The lower noise levels separating the hot spots in the experiment are partly caused by the sting support which was covered by non-reflecting foam and is not present in the simulation which does not include such a device.

![Figure 9: HART II mid-frequency noise level.](image)

![Figure 10: Noise carpet based on S4 simulation.](image)
4.4 Wake position

Wake positions were determined within HART II by PIV analysis. The coordinates of the vortex centers found within the PIV velocity vector maps, together with the coordinates of the PIV frame in the wind tunnel and the hub center in the same coordinate system, define the vortex position with respect to the hub center. At y/R = 0.7 the vortex was traced downstream on the advancing side from its creation behind the trailing edge until leaving the disk. The same data can be obtained from the prescribed wake used within the S4 code. In addition, the blade tip was measured by SPR (see Figure 6) and its positions at the front of the disk (135deg azimuth) and at the rear (45deg azimuth) for this lateral position can be extracted. The wake trajectory must fit to the blade position where it was created.

The results are also compared to the basic Beddoes wake geometry in order to get a feeling for the wake geometry upgrades in the S4 code. All these data are put together in Figure 11. On the advancing side, the vortex passes high above the disk in the second quarter (x<0), but then quickly convects downwards (x>0) and passing the blade tip path plane at about x/R = 0.75 to generate BVI in the vicinity of this location, which can be seen also in Figure 5.

The magnitude of vertical convection is not predicted correctly, but the BVI location is acceptable. It is remarkable that the original Beddoes geometry is matching the BVI location at both sides in a similar quality, just the vertical wake deflection magnitude is significantly below the S4 results.

![Figure 11: Wake trajectories at y/R = 0.7 (top) and y/R = -0.7 (bottom).](image-url)

5. CONCLUSIONS

This code validation demonstrates the capabilities of today’s state-of-the-art comprehensive codes with respect to rotor blade dynamics, section aerodynamics and noise radiation. Provided that all sub-models are of the required level of detail quite acceptable results are obtained for all these aspects. The requirements are:

- fully elastic blades in flap and torsion
- unsteady aerodynamic formulation, separating for rigid body motion and the gust problem
- a wake geometry that accounts for fundamental effects of dynamic rotor loading

ACKNOWLEDGMENTS

The authors like to acknowledge the cooperation of the HART II team during the preparation, acquisition and post-test phase of the HART II test. Data are available on the HART II FTP site for code validation purposes, which is open to the international rotorcraft community via the International HART II Workshop.

REFERENCES

[8] International HART II Workshop held semi-annually at the AHS and ERF conferences, ftp://HART-II@ftp.dlr.de, password: HART-II

