PAPER Nr.: 115

HHC Aeroacoustics Rotor Test at the DNW - The Joint German/French/US HART Project -

Yung H. Yu
Aeroflightdynamics Directorate(AFDD)
US Army Aviation and Troop Command (ATCOM)
Moffett Field, CA. USA

Bernd Gmelin
Institut für Flugmechanik

Hanno Heller
Institut für Entwurfsaerodynamik

Deutsche Forschungsanstalt für Luft-und Raumfahrt (DLR)
Braunschweig, Germany

Jean J. Philippe
Office National D'Etudes et de Recherches Aerospatiales (ONERA)
Chatillon, France

Edzard Mercker
Duits-Nederlandse Windtunnel
Noordoostpolder, The Netherlands

John S. Preisser
NASA Langley Research Center
Hampton, VA. USA

TWENTIETH EUROPEAN ROTORCRAFT FORUM
OCTOBER 4 - 7, 1994 AMSTERDAM

HHC Aeroacoustics Rotor Test at the DNW - The Joint German/French/US HART Project -

Yung H. Yu
Aeroflightdynamics Directorate(AFDD)
US Army Aviation and Troop Command (ATCOM)
Ames Research Center, Moffett Field, CA.

Bernd Gmelin
Institut für Flugmechanik
Deutsche Forschungsanstalt für Luft-und Raumfahrt (DLR)
Braunschweig, Germany

Hanno Heller
Institut für Entwurfsaerodynamik
Deutsche Forschungsanstalt für Luft-und Raumfahrt (DLR)
Braunschweig, Germany

Jean J. Philippe
Office National D'Etudes et de Recherches Aerospatiales (ONERA)
Chatillon, France

Edzard Mercker
Duits-Nederlandse Windtunnel (DNW)
Noordoostpolder, The Netherlands

John S. Preisser
NASA Langley Research Center
Hampton, VA

Abstract

In a major cooperative program within existing US-German and US-French Memoranda of Understanding(MOUs), researchers from the German DLR, the French ONERA, NASA Langley, and the US Army Aeroflightdynamics Directorate (AFDD) conducted a comprehensive experimental program with a 40%-geometrically and aeroelastically scaled model of a BO-105 main rotor in the open-jet anechoic test section of the German-Dutch Windtunnel(DNW) in the Netherlands. The objective of the program was to improve the basic understanding and the analytical modeling of the effects of the higher harmonic pitch control technique on rotor noise and vibration reduction. Comprehensive acoustic, aerodynamic, dynamic, performance, and rotor wake data were obtained with a pressure-instrumented rotor blade. This international cooperative project carries the acronym HART (Higher-harmonic-control Aeroacoustics Rotor Test). An overview of this HART program is given in this paper along with some representative experimental and analytical results.

Introduction

Among several helicopter noise generating mechanisms, blade-vortex interactions (BVI) cause one of the most annoying and intrusive kinds of noise and become dominant during low speed descent and maneuvering flight, where the rotor wake is blown back into the rotor plane. Because of the dependence of BVI on the complex geometrical structure of the wake, blade-vortex interaction is extremely sensitive to rotor design and helicopter operating conditions.

Current research efforts in Europe and the US have indicated a potentially high payoff for impulsive BVI noise and vibration reduction by the application of higher-harmonic blade pitch control(HHC) techniques. Although originally designed and developed for vibration reduction purposes (where this technique showed excellent results), wind tunnel tests and flight tests have shown BVI noise reduction of up to 6 dB, while vibration and low-frequency noise levels were increased. However, with certain HHC schedules (amplitude and phase), the simultaneous reduction of noise and vibration has been achieved. But, more detailed knowledge is necessary to understand and explain the apparently adverse behavior of and potential benefits on noise and vibration when HHC is applied. Since current physical understanding of the HHC effect on noise and vibration reduction is still limited, the full potential of the technique has not been fully utilized. For further applications of this technique, the international rotorcraft research community has recognized the essential need for the development of analytical prediction capabilities and for a comprehensive database.

More than 10 years ago, within the auspices of the joint Memorandum of Understanding(MOU) between the United States and France, an AH-1/OLS scaled model rotor test was performed in the French CEPRA-19 wind tunnel (Ref.1). Subsequently, the same rotor was tested as a first rotor test in the German-Dutch Windtunnel (DNW) under another MOU between the United States and Germany (Ref.2) It was this benchmark test which eventually led to the active MOU activities on rotor aeroacoustics among participants and furthermore to performing this joint cooperative multi-national program, called Higher-harmonic-control Aeroacoustics Rotor Test (HART) program, with a scaled model of the BO-105 rotor system. Two teams were formed to efficiently carry out the program: a test team and a prediction team, consisting of researchers from each participating organizations. The test team has the responsibility of carrying out the test in the DNW and of data acquisition/analysis. The overall test coordination is rested with the DLR-Design Aerodynamics. The responsibility of each organization is as follows.

DLR - Flight Mechanics :
basic rotor rig, model rotor, HHC control system,
rotor system instrumentation,
rotor/wind tunnel data acquisition, and on-line analysis
- Design Aerodynamics :
traversing microphone array,
pressure-instrumented rotor blade,
acoustic data acquisition and on-line analysis
overall test coordination

- Aeroelasticity :
  blade pressure data acquisition and on-line analysis
- Fluid Mechanics :
  LDV in the advancing side for vortex strength and core size measurements,

ONERA : LDV in the retreating side for vortex strength and core size measurements, blade tip deflection measurements

DNW : LLS flow visualization for vortex trajectory and blade-vortex miss distance measurements projected-grid method for blade deformation

AFDD : DNW test time overall program responsibility

From previous analytical and experimental work of BVI noise and vibration reduction, the following parameters were identified to control the BVI noise and vibration: tip vortex core size, tip vortex strength, tip vortex geometry, miss-distance, and blade deformation. Therefore, a test plan has been generated to measure these parameters. That is, acoustics with a microphone array, blade surface pressure with miniature pressure transducers, tip vortex trajectories and blade-vortex miss distance with a laser light sheet (LLS) flow visualization technique, vortex strength and vortex core size with a LDV technique, and blade deflection/attitude with Projected Grid Method (PGM) and videographic method, totaling of 22 days of the test.

Meanwhile, the prediction team, coordinated by AFDD, was also formed with researchers from DLR, ONERA, NASA-Langley, and AFDD to develop their own prediction capability in acoustics, aerodynamics, wake geometry, and blade deformation. This prediction team was actively involved with the pre-test activities of the test team to define the test matrix and the measurement approaches of the experimental techniques. Specifically, the prediction team activity was (1) to correlate its predicted results with the existing DNW experimental data from the AH-1/OLS test and the earlier BO-105 model test, (2) to predict the HART test results in advance. This will ensure getting the best quality of test data and the necessary information for the code validation, which has been the major problem for the most code-test data correlation activities in the past.

In summary, the main objectives of this HART program were (1) to investigate the physics of BVI noise and vibration reduction concepts with the HHC technology, (2) to develop an analytical prediction capability for BVI noise with HHC inputs, and (3) to generate an experimental data base for code validation. With these objectives, the joint international cooperative HART program was initiated under the auspices of the existing US/German and US/France MOUs and a test with the BO-105 model rotor was successfully performed at the DNW in June, 1994. All the original objectives have been completely satisfied beyond all expectations.

In this paper, a general overview of the HART program and some representative experimental and predicted results are given. Many details of each technical areas will be presented by the participants in the coming years.

Test Facilities

The DNW is the world's largest acoustic wind tunnel and has outstanding aerodynamic and acoustic properties, offering low background noise. The DNW has become a major rotorcraft aeroacoustic testing facility. All the data acquired for this program were taken in the 6.0 by 8.0 m open-jet configuration, where flow velocities of up to 80 m/s (262.5 ft/sec or 155 knots) can be reached. An acoustically treated testing hall of more than 30,000 cubic meter surrounds the open-jet testing configuration. This results in exceptional anechoic properties (the cutoff frequency is 80 Hz). The tunnel also has excellent flow qualities, since the flow uniformity is quite high and the unsteady disturbance amplitude is quite low over the total testing velocity range.

The BO-105 model rotor was positioned on the vertical and lateral centering of the DNW test section, and up one meter from the longitudinal centerline.(Fig.1) This position enabled acoustic measurements for the acoustic traversing mechanism located inside of the tunnel shear layer. The newly designed rotor test rig ROTEST II features high-frequency hydraulic rotor control actuators for the higher harmonic rotor control. It also features additional devices to pre-amplify and to transmit the signals of the blade pressure transducers and others from the rotating to the fixed frame.(Refs. 3 and 4). The test rig contains the hydraulic drive system, the rotor balance, and was supported by the computer-controlled, hydraulically actuated model sting support mechanism of the DNW.

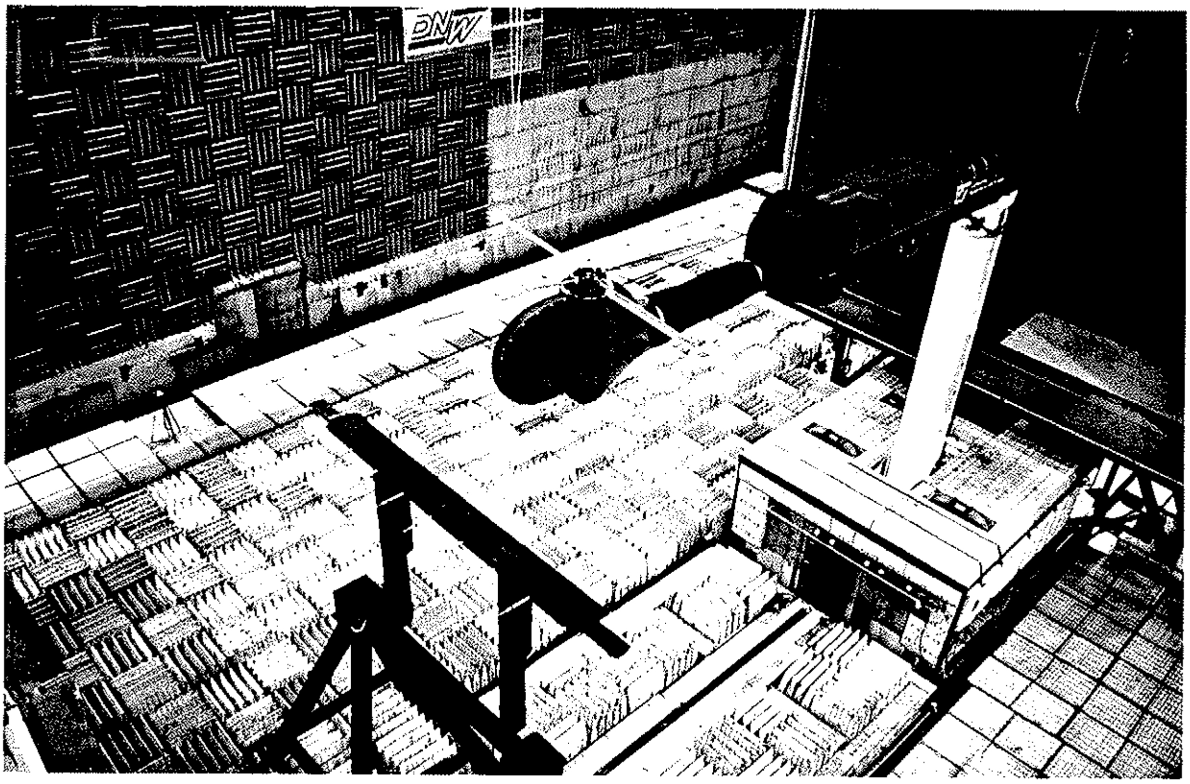

Fig. 1 BO-105 model rotor in the DNW

Pressure-instrumented Rotor Blades

The rotor is a 40%-geometrically and dynamically scaled model of the 4-blade, hingeless BO 105 main rotor of 4 m diameter and 0.121 m chord length.(Fig.2) The rotor blade uses a NACA 23012 airfoil with the trailing edge modified to form a 5 mm long tab to match the full-scale rotor. The blade has - 8 deg. of linear twist, a square tip, and a solidity of 0.077. The nominal rotor operational speed is 1040 rpm, giving a blade passage frequency of 70 Hz. The nominal hover tip Mach number is 0.641. More detailed information on the rotor characteristics is given in Ref. 4 and 5.

One of the rotor blades was equipped with a total of 124 specially configured miniature absolute pressure transducers of the piezoresistive type, mainly installed at three blade spanwise locations (r/R = 0.75, 0.87, and 0.97) with up to 44 sensors each per cross section. The typical response was flat within 1 dB up to 7 kHz with a resonance occuring beyond 10 kHz. The pressure instrumented blade was also equipped with 32 strain gauges. The other three blades were equipped with seven strain gauges each and one of them has three temperature sensors. Flapwise, edgewise, and torsional strains were measured at up to 16 radial stations between r/R = 0.14 and 0.83.

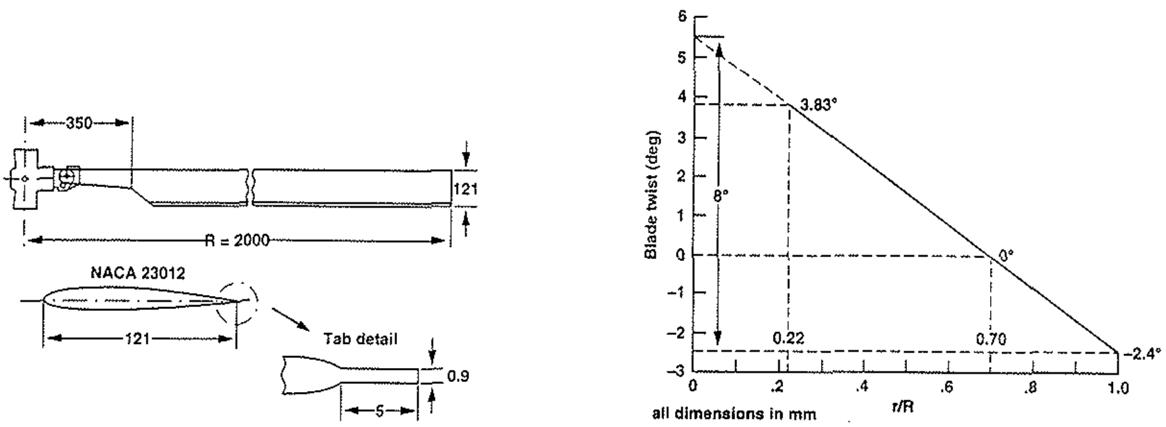

Fig. 2 Model Rotor Blade Geometry

Data Acquisition Systems

The overall DLR data monitoring and acquisition system is diagrammed in Fig.3 in which the measurement procedures of the wind tunnel data, rotor performance data, blade pressure and strain gauge data, and acoustic data are described. The individual acquisition systems of DNW and DLR were all computer-controlled and linked together via ETHERNET except the blade pressure measuring system which was linked indirectly via RS 232 to the rotor performance acquisition system. (Ref. 4) The stability and steadiness of the test conditions as well as the consistency and repeatability of the measurement results were carefully verified during the test period by acquiring a number of check points with identical test conditions.

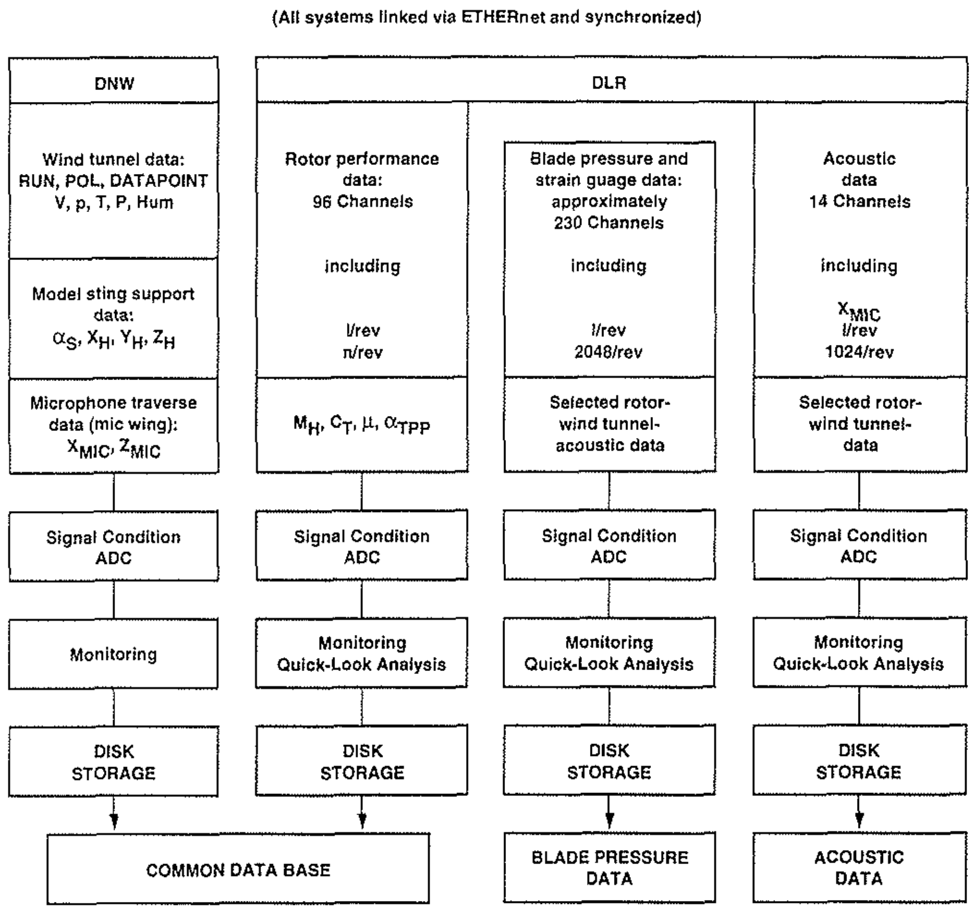

Fig. 3 DLR Data Monitoring and Acquisition System

Test Conditions

The test matrix represents a number of simulated flight conditions of descent. Major emphasis was put on rotor conditions known to generate blade-vortex interaction noise. For a typical BVI condition with and without HHC inputs, extensive measurements of vortex strength, vortex core size, miss distance, and blade deformation during interactions were made to investigate the effects of wake systems and blade dynamics on acoustics. The test cases are as follows:

A. Aeroacoustic Tests : blade surface pressure and acoustic measurements with/without HHC

A1. hover test
A2. HHC variations - baseline, low-speed bvi, high-speed bvi
A3. operational variations - wind speed, shaft angles
A4. full-scale correlation test - different trim conditions

B. Flow Visualization Tests : vortex trajectories and blade/vortex miss distance (adv. and retreating sides)

B1. typical bvi conditions - baseline, low noise, low vibration
B2. shaft angle variation

C. LDV Measurements : vortex velocity distribution, circulation strength, and core size

C1. typical bvi conditions - baseline, low noise, low vibration
C2. shaft angle variation

D. Blade Deflection and Tip Deflection Measurements :

D1. typical bvi conditions - baseline, low noise, low vibration
D2. shaft angle variation
D3. higher thrust

The more details of the test conditions are given in Ref. 12.

Measurements and Results

The measurement techniques of acoustics, airload, miss distance, vortex structures and core size, and blade deflection and attitude are discussed along with some representative test data.

Acoustics :

The acoustic measurements were made with the array of eleven microphones mounted on a ground based traverse system with a maximum range of 11 m in flow direction. (Fig.1) This microphone array was moved slowly (45 mm/sec) and continuousely over the measuring range of typically 4 to 5 R. The array vertical position was 2.3 m (1.15 R) below the rotor hub. In addition to this array, there were three fixed-position microphones, two of which were located in the plane of rotation in 1.7 R away. The details of acoustic data acquisition and analysis techniques are in Ref. 4.

The excellent aerodynamic flow quality and acoustic properties of the DNW contributes to both the consistent steadiness and repeatability of the acquired acoustic data. Wind tunnel background noise measurements at different airspeeds were taken to ensure a proper signal-to-noise ratio. (Ref. 5)

Acoustic and vibration measurements were made where prescribed, open loop HHC pitch schedules were superimposed on the normal (baseline) collective and cyclic trim pitch. Typical blade-vortex interaction noise characteristics for a low speed 6 deg. descent condition are shown in Fig.4, indicating high intensity noise radiation lobes in advancing and retreating sides. Even though the pressure response on the retreating side is much stronger than those on the advancing side, the BVI noise is seen to be weaker in intensity on the retreating side. The power spectra also illustrated the impulsive nature of BVI noise and is mainly distributed in the mid-frequency range approximately between the 6th and the 40th blade passage frequency harmonics as reported in previous work(Ref.5-8,13). Strong changes in BVI noise directivity and intensity are observed at different flight conditions, demonstrating that the wake system plays a very important role.

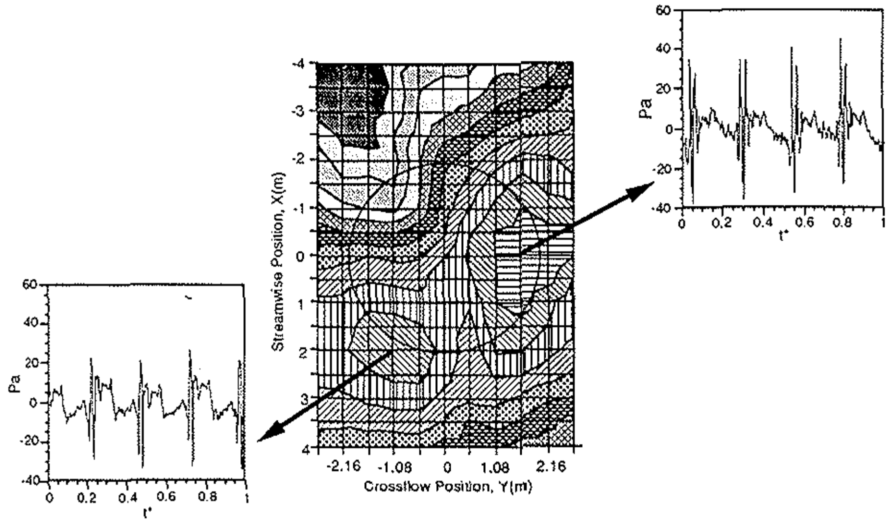

Fig. 4 Typical BVI Noise Footprint without HHC inputs

Significant mid-frequency noise reduction of 4-6 dB is shown in Fig.5, as also reported in Ref. 6 and 7, for low-speed descent conditions where BVI is most intensive. The noise reduction may be attributed to the modified vortex structures including strength and miss distance during the interactions through the HHC blade pitch control. The amplitude and phasing of such pitch controls may be expected to play an important role in the noise reduction, since the strongest blade-vortex interactions tend to be located within small azimuthal angle ranges.

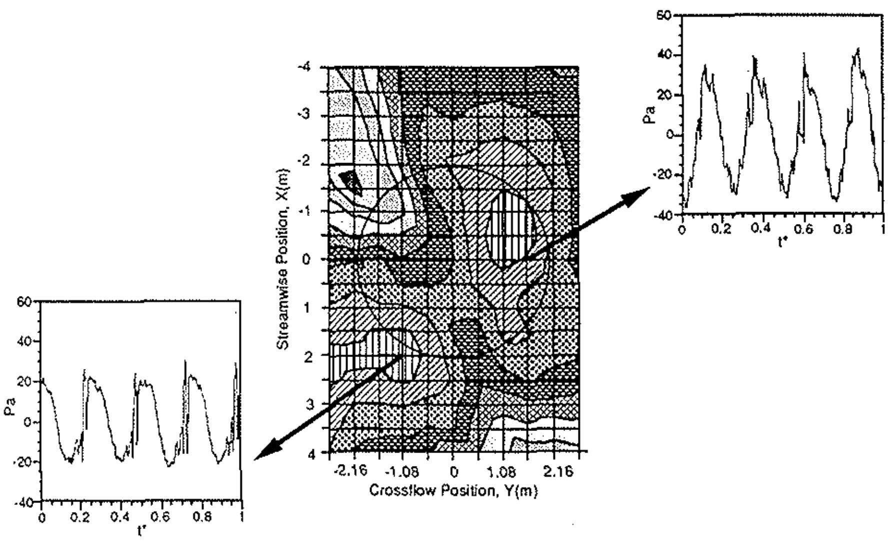

Fig. 5 Typical BVI Noise Footprint with HHC Inputs

Airload:

A specially configured 352-channel TEDAS (transputer based expandible data acquisition system) was developed by DLR, which was composed of 44 intelligent data acquisition modules (IDAMS). Each module consists of a transputer(T800), 4 MByte RAM and eight 16-bit A/D-converters of 44 kHz sample frequency. Data pre-processing with TEDAS was very time-efficient since all transputer modules were working in parallel, so that shortly after the test the averaged measured data of 64 rotor revolutions were available for display and plotting.

Time averaged blade surface pressure coefficients show impulsive pressure fluctuations due to BVIs on the advancing and retreating sides. Mostly, these pressure fluctuations are concentrated near the blade leading edge, as observed in the previous work. With certain HHC inputs, the blade surface pressures show drastic changes, especially at the blade tip, which can develop negative lift and twin vortices of the opposite sign. Local blade airloads were calculated by integration of the measured blade pressures at each radial station. Time histories of normal force multiplied by the Mach number squared for a 6 deg. descent condition are shown in Fig.6. Impulsive load fluctuations due to BVI on the advancing and retreating sides are quite obvious. Further results pertaining to BVI impulsive loads are discussed in more details in Ref. 5,11 and 14.

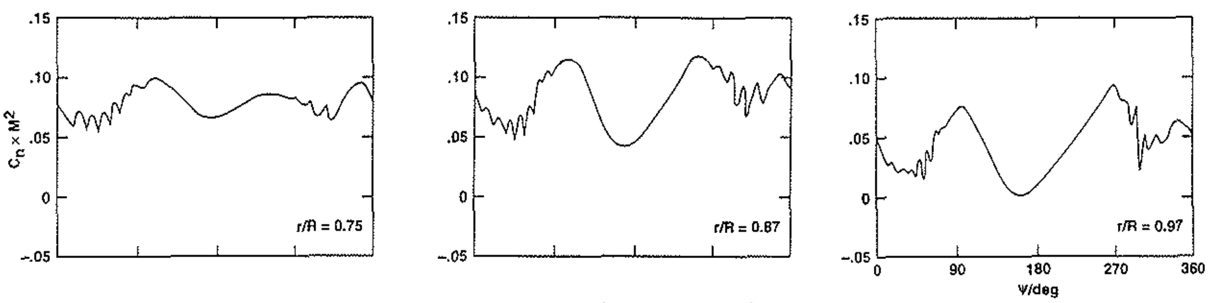

Fig. 6 Local Blade Airloads

Miss Distance :

A laser light sheet (LLS) technique with a 5 W laser light sheet and a triggerable video camera together with a stroboscope light source(Ref.9) was used to measure the miss distance between tip vortices and a blade path plane of a model rotor on the advancing and retreating sides. A reference grid was recorded with the same video camera, which was used as an overlay on the actual flow visualization pictures. This leads to the evaluation of the position of the blade tip vortices in space relative to a passing blade as shown in Fig.7. Furthermore, the miss distance between a vortex and the blade path plane can be determined. Fig. 7 also shows that the acoustically most important BVI occurs at the azimuthal angle of about 50 deg. During this interaction, the tip vortex is passing through the blade path plane. Due to this close interaction with a blade, the vortex induces large pressure fluctuations over the blade leading edge, which generates impulsive noise. Additional interactions occur with other vortices at different azimuthal angles, but these are acoustically less effective.

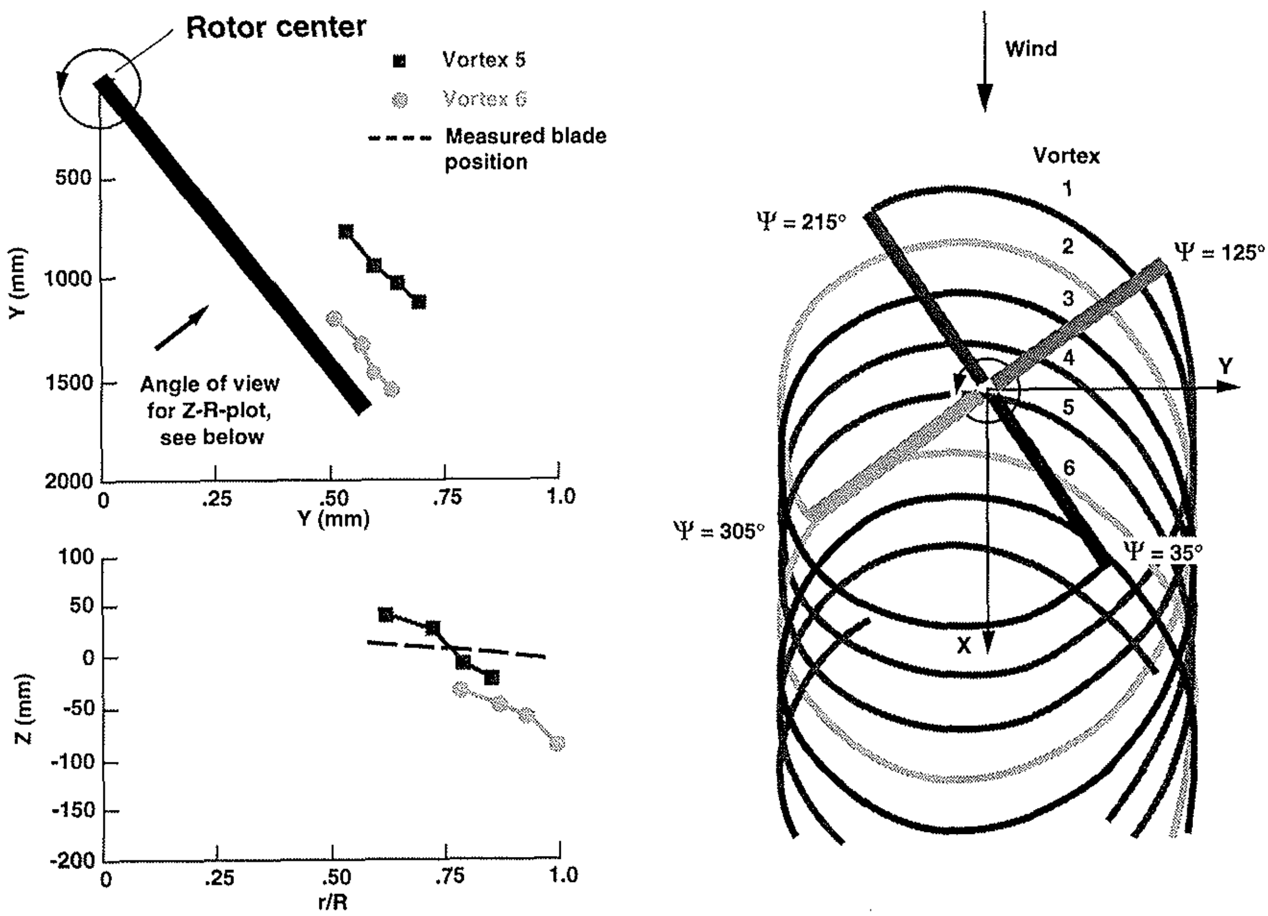

Fig. 7 Rotor Vortex Geometry and Miss Distance

Vortex Structures and Core Size :

Two 3D laser velocimeter systems have been installed on a platform 9 m high in the test area to measure the vortex structures and core sizes on advancing and retreating sides. On the advancing side, a 6 watts Argon-Ion laser with a 5 m working distance was installed by the Institute for Fluid Mechanics of DLR. Three most intensive light beams (green 514.5 nm, blue 488 nm, violet 476.5 nm) were used to measure the velocity components. Each beam was devided into two individual beams, one of which was superimposed with a Bragg shift of 40 MHz.. The effective size of the probe volume was about 0.25 mm in diameter and 1 mm in length. Particles consisted of dispersed oil, having a maximum size of 1 μ m or smaller, and these are small enough to faithfully follow the flow. The receiving optics, operating in a back-scalttering mode, requires a large elliptical mirror of a 500 mm aperture to gather enough scattered light. The three signals were then processed by a DSA 3220 from Aerometrics which enables obtaining the velocity vector of each particles as shown in Fig. 8.

The vortex structure at 300 deg. of the azimuthal angle on the retreating side has been investigated by an ONERA 3D laser velocimeter, which has a 5 m working distance. In the probe volume of 400 μ m wide, three fringe patterns (green 514.5 nm, blue 488 nm, violet 476.5 nm) were created with two powerful Argon lasers of 10 and 2 watts. Flow was seeded with 0.5 μ m particles of incense smoke which was injected into the flow from the settling chamber with a remote-controlled mechanical traverse system. Scattered light crossing the probe volume was collected in a backscatter mode by a 450 mm aperture Cassegrain telescope with three photo- multipliers. The three signals were then processed by an IFA 750 which enables obtaining the instantaneous velocity vector of each particle. Therefore, the mean velocities of the flow field, the vorticity distribution and the turbulence levels such as RMS values and shear stresses are obtained. A typical mean velocity distribution of the flow field is obtained within half an hour(Fig.9), from which the information of the vortex core diameter and the vortex intensity can be obtained.

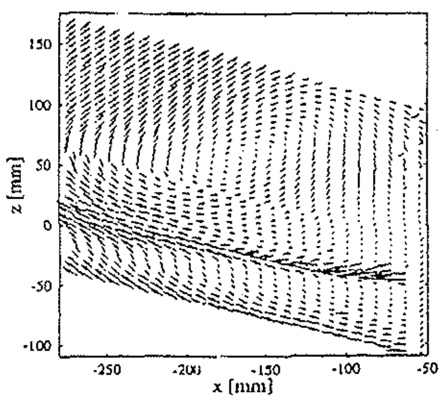

Fig. 8 Velocity Map of Vortex in Advancing Side

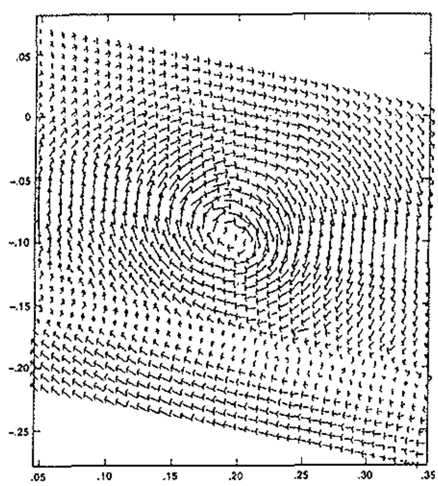

Fig. 9 Typical Mean Velocity Distribution in Retreating Side

Blade Deflection and Attitude:

For a detailed analysis of blade-vortex interactions, it is essential to gain some knowledge about the deformation of a rotor blade due to aerodynamic loadings at different azimuth angles. For this purpose DNW developed a dedicated photonical method to evaluate the blade deflection during interactions. The principle method is the so-called projected grid method (Ref. 15), where a grid is projected on the blade surface which is deformed or displaced out-of-plane. Looking from a direction which differs from the projection direction, the displacement of the blade can be evaluated from the characteristics of the grid image.

The application of this method for operating rotors required that the blades were painted dull white and the testing chamber was darkened. The recordings of the blade in motion were carried out with a triggerable high resolving-power CCD camera. Furthermore, the grid images were processed separately and subsequently the results of the separate digital image processing were subtracted from each other in order to obtain quantitative information. In this way, the pre-twist and the precone angle of the blade were automatically taken care of.

Additionally, for easier data interpretation the grid was projected perpendicular to the leading edge of the blade (the projection of the grid in this way yields that a parallel shift of the grid pattern is equivalent to a vertical displacement of the blade, whereas a skewed shift of the grid lines occurs due to blade torsion). This was achieved by installing a specially constructed optical bench underneath the rotor. With the center of rotation aligned vertically with the rotor center the optical bench could be rotated over 360 degrees. At a pre-selected fixed position of the bench, recording of the grid pattern was possible at the desired azimuthal rotor angle by triggering the video camera adequately.

Fig.10 shows a comparison of different HHC settings for a rotor blade at an azimuthal angle of 60 degrees. For the baseline case, which was taken as a reference, no HHC was applied. For a low noise case, the blade is deflected upwards, generating weak interactions with the tip vortices. The opposite trend is observed for the low vibration case, where the HHC setting was adjusted to receive the low vibration level at the rotor shaft. In this case, the blade is deflected downwards, generating strong interactions with the tip vortices passing through the rotor plane. It is interesting to note that in this case the overall sound pressure level is higher than the level for the baseline case and a negative aerodynamic loading is observed at the blade tip at an azimuthal angle of around 130 deg. This negative loading at the blade tip generates two counter-rotating tip vortices instead of one commonly observed. Fig. 10 also shows the torsional angles of the blade for the different HHC settings with respect to the baseline case. From these results, the torsional deformation of the blade along the span can easily be obtained.

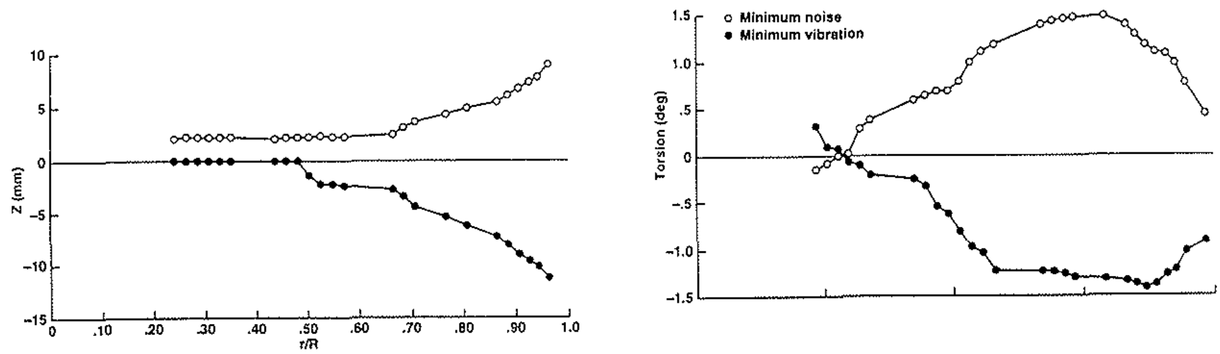

Fig. 10 Blade Deflection and Torsional Distribution Along the Span

The blade tip deflection has been measured using a Target Attitude in Real Time (TART) method, which the images of two reflecting points on the blade tip are recorded at each rotation on a stroboscopic CCD camera. The variations of the blade flapping, lead-lag and pitching of the blade tip are measured as a function of time with a resolution of a few tenths of a millimeter and a few hundredths of a degree. This method has been successively applied at several azimuthal angles and its results are in good agreement with those measured by other methods.

Analytical Capability Developements and Results

As part of this cooperative program, aerodynamic and acoustic prediction codes have been developed by each participating organization with the emphasis to the understanding of BVI noise generating mechanisms with and without HHC blade pitch controls.

The German DLR uses the aerodynamic code, S4, to predict the performance, rotor dynamics, and unsteady blade loading, and AKUROT code for acoustic predictions. The French ONERA uses MESIR and MENTHE for the rotor free wake geometry, ARHIS or FP3D code for the blade surface pressure field, and PARIS for acoustic predictions. The ARHIS code is based on a two dimensional singularity method with inviscid and incompressible flow along with compressibility corrections. NASA Langley uses a rotor performance code with free wake and blade dynamics models, CAMRAD.Mod 1, which is an enhanced version of the CAMRAD code. A high resolution post processing code, called HIRES, is coupled with CAMRAD.Mod 1. The unsteady full potential code, FPRBVI, is alternately coupled with CAMRAD.Mod 1 to provide blade pressure prediction. With the inputs from FPRBVI/HIRES, the acoustic code, WOPWOP, was used for acoustic predictions. Furthermore, wind tunnel wall corrections and fuselage effects are also considered in the analysis. The US Army AFDD uses the Full Potential Rotor (FPR) code and CAMRAD/JA for airload predictions, and RAPP (Rotor Acoustic Prediction Program) code for acoustic predictions. All the acoustic codes used in the program, RAPP, AKUROT, PARIS, and WOPWOP, are based on the linear thickness and loading terms of the Ffowcs Williams and Hawkings (FWH) formulation. More details about these various prediction codes and its capabilities are described in Refs. 10 and 11. With these codes, a joint validation effort has been already performed with two existing DNW rotor test data: one with AH-1/OLS data (Ref. 10) and the other with BO-105 data.(Ref. 11)

The new HART test data is carefully being examined to understand the BVI noise generation mechanisms with HHC inputs for flight conditions where the BVI noise is normally intense and at the same time to validate the analytical prediction capabilities. To help give insight to the physics of the HHC/BVI noise problem, the predicted results of airload, noise, vortex structures, and blade aeroelastic deformation are compared with the test data.

A few examples from the joint international prediction effort are shown here with the test data. A typical acoustic footprint is shown in Fig.11 with predicted results from four participating organizations, showing strong BVI noise patterns on both the advancing and retreating sides as expected. The time history signatures for a given microphone position are also shown in Fig.12, where strong noise pulse peaks due to BVIs are fairly well predicted as compared with the test data. The airload predictions along the azimuthal angle show the strong BVIs on the advancing and retreating sides and the predicted results are matched very well with the experimental data as shown in Fig.13. Other parameters such as the miss distance and the blade aeroelastic deformation were predicted and also compared with the experimental data. More details on these correlation efforts will be reported later by participating researchers.

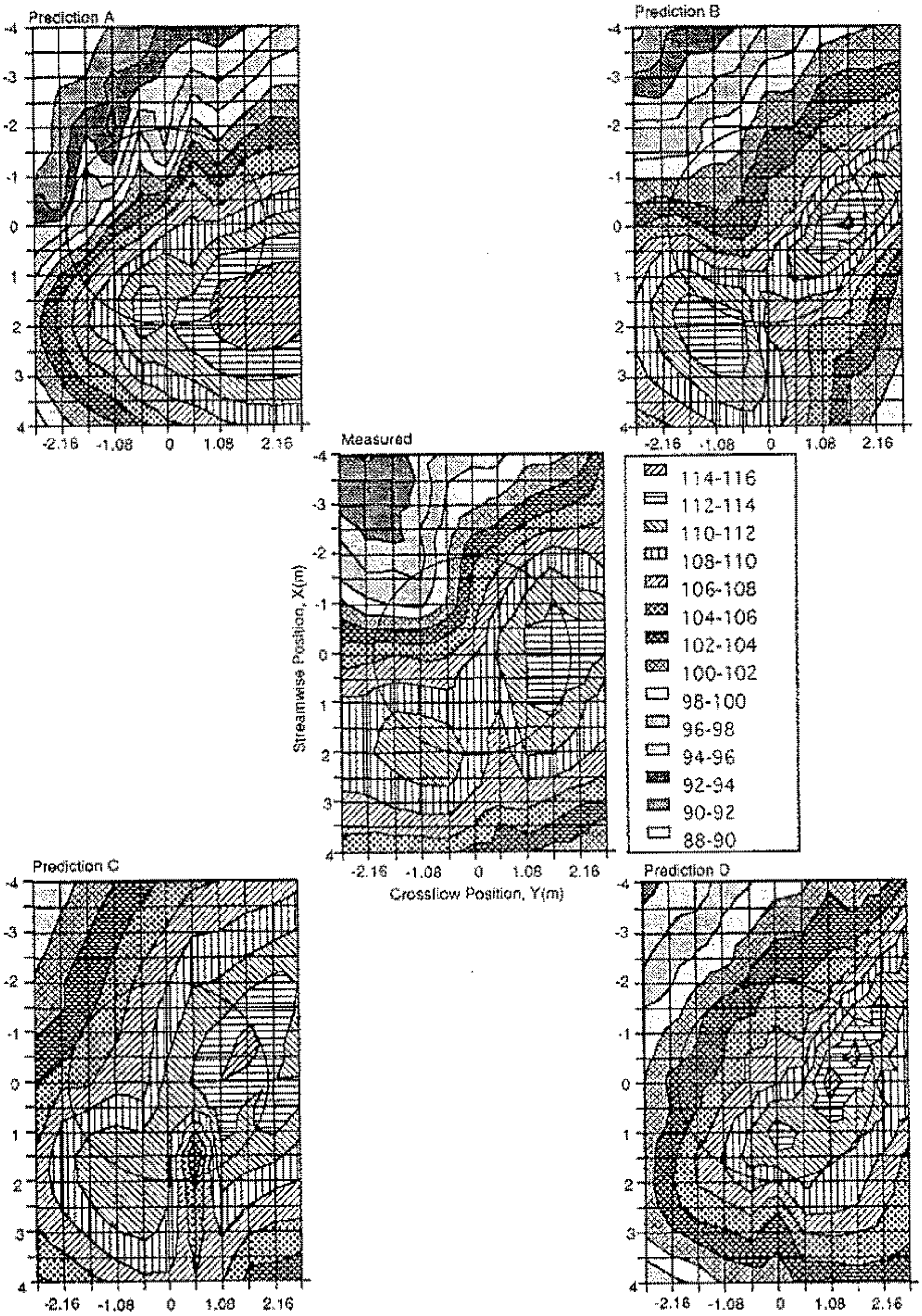

Fig. 11 Correlation of Predicted Results with Acoustic Footprint Data

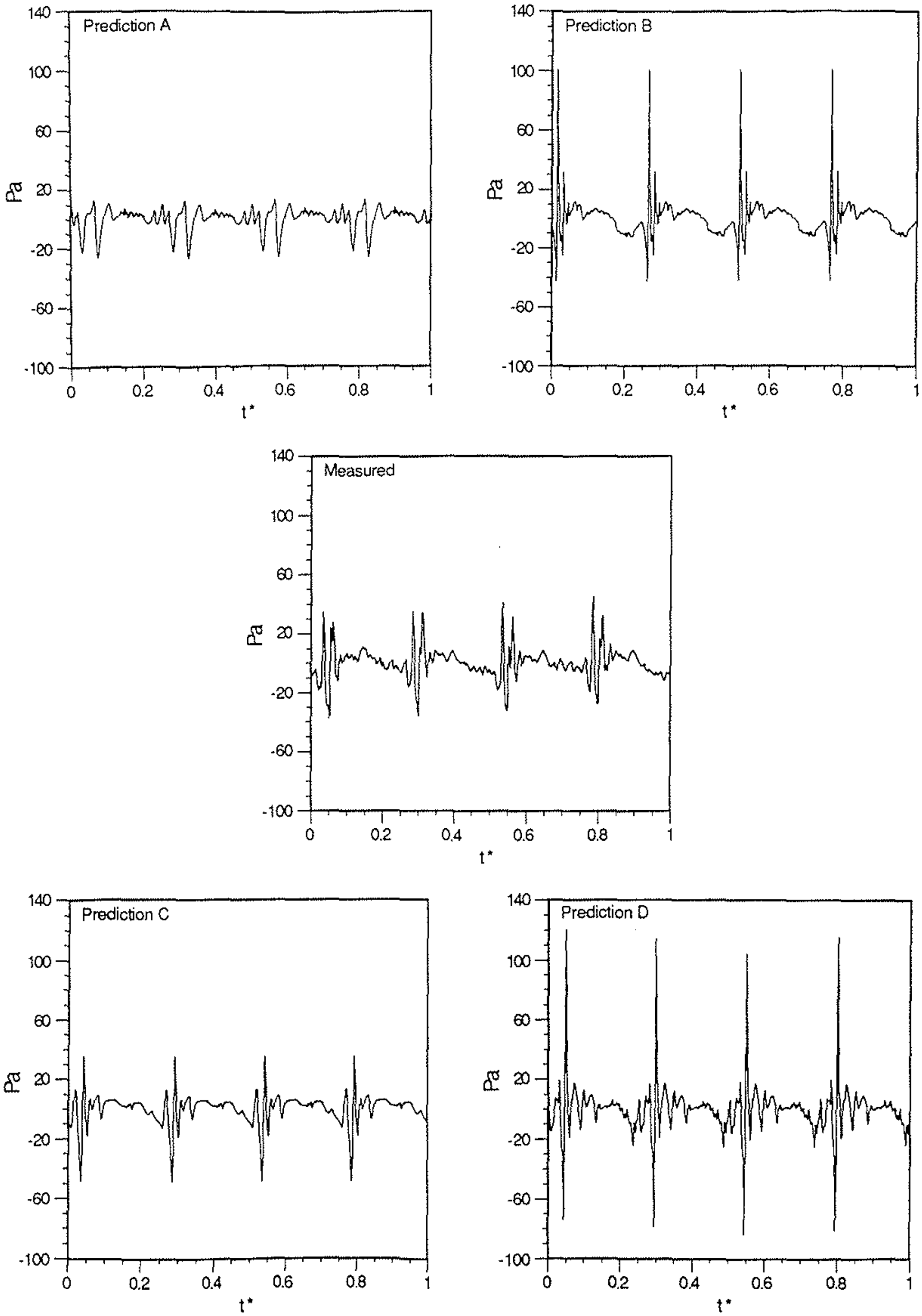

Fig. 12 Correlation of Predicted Results with Acoustic Test Data

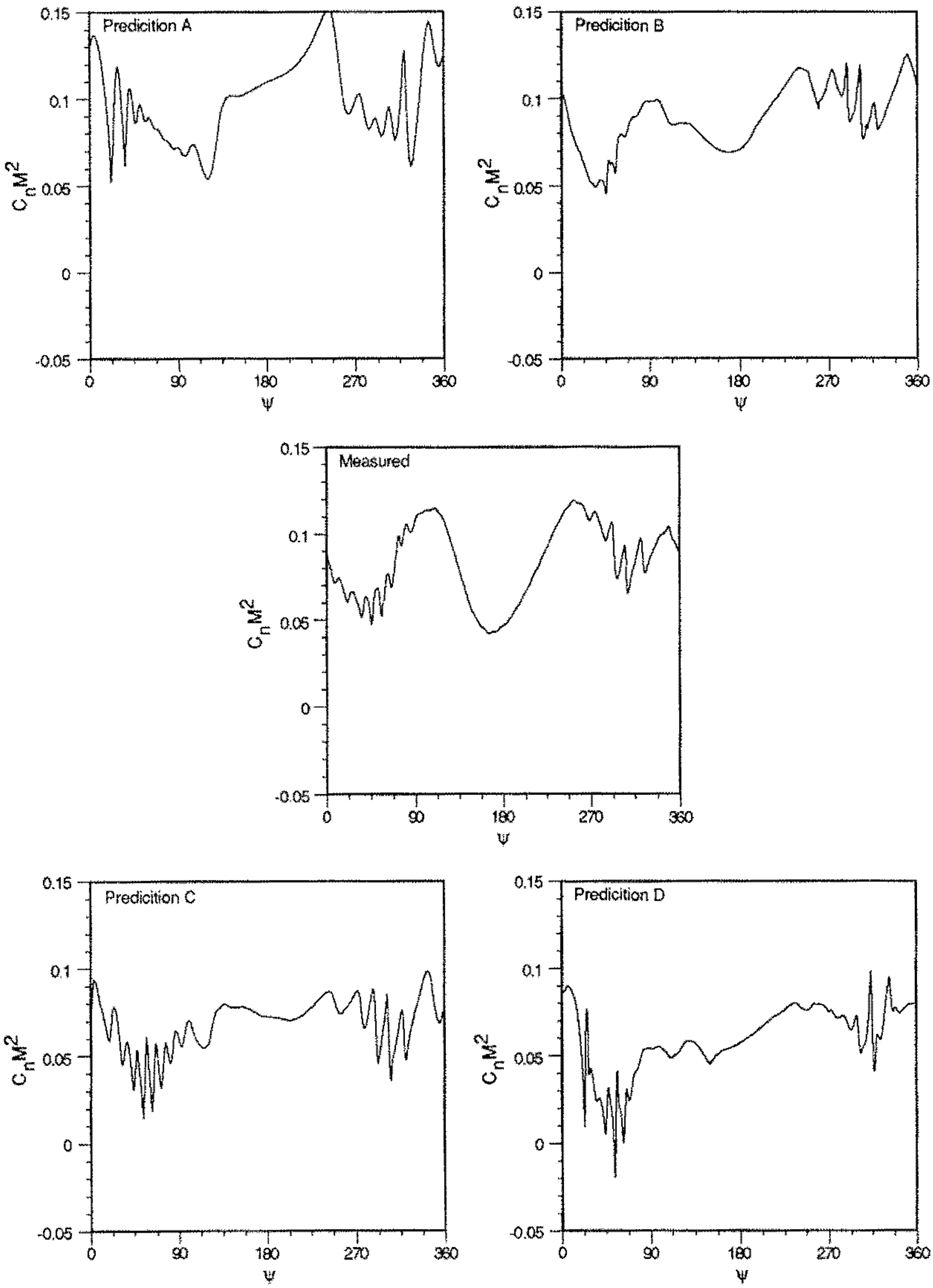

Fig. 13 Correlation of Predicted Results with Airload Test Data

Concluding Remarks

A joint international cooperative program has been successfully performed with the German DLR, the French ONERA, the German-Dutch DNW, US NASA Langley, and the US Army AFDD to pursue the same technical goals with the combined effort of manpower, expertise and financial resources. This program has several "firsts" of important events: first time to simultaneously measure the acoustics, aerodynamics, wake systems, and blade deformation of a rotor to investigate the HHC effects on noise and vibration reduction, first time to predict the test data in advance and correlate the predicted results with the test data on the test site every day, and first time for several international research organizations to work together to achieve the same technical goals.

The HART test at the DNW consists of measurements of acoustics with the microphone array, blade surface pressure with 124 miniature pressure transducers, vortex strength and core size with LDV systems, miss distance with a LLS technique, blade deformation with a projected-grid method, and blade tip deflection with an optical technique. This data base is extremely valuable and will substantially help the research community for prediction code validation effort and understanding of the BVI phenomenon.

Acknowledgment

A wind tunnel test at the DNW with a rotor system such as this HART test needs lots of devoted and talented researchers,engineers, mechanics, technicians, and managers. We all appreciate the unselfish devotion of many people to make this program so successful. In particular, very special appreciation goes to Dr. Wolf Splettstoesser of DLR-Design Aerodynamics,Braunschweig for his unselfish devotion to the program as Test Director. Here are a few names of the devoted contributors:

Philippe Beaumier, Peter Bögershausen, Alain Boutier, Gunter Braun, Tom Brooks, Casey Burley, Gerhard Buschbaum, Albert Demargne, Susanne Ehr, Judy Gallman, Wolfgang Geissler, Florian Jansen, Bernd Junker, Roland Kube, Gerhard Kwapis, Dieter Mätzing, Christian Meyer, Hans Günter Nolle, Jacq. van Nunen, Kurt Pengel, Jean Prieur, G. Rahier, Michael Roth, Ulrich Seelhorst, Pierre Spiegel, Wolf Splettstoesser, Klaus Schultz, Dieter Tobschall, Edward Tomm, Chee Tung, Wolfgang Wagner, Berend van der Wall, Erik Wirth, Hans-Jürgen Wirth, Hans-Joachim Worbs, and the DNW crews.

REFRENCES:

1. Schmitz, F.H., Boxwell, D.A., Lewy,S., and Dahan C., " A Note on the General Scaling of Helicopter Blade-Vortex Interaction Noise," American Helicopter Society 38th Annual National Forum, Anaheim, CA, May 1982

2. Splettstoesser, W. R., Schultz, K.J., Schmitz, F.H., and Boxwell, D.A., "Model Rotor High Speed Impulsive Noise - Parametric Variations and Full-Scale Comparisons," American Helicopter Society 39th Annual National Forum, St.Louis, Missouri, May 1983

3.Kube, R.,"Simultaneous Vibration and BVI Noise Feedback for Closed Loop Higher Harmonic Control: Influence of Rotor Dynamics on Controller Design," presented at the 19th European Rotorcraft Forum, paper no. G15, September 14-16, 1993, Cernobbio, Italy

4. Splettstoesser,W.R., Niesl,G., Cenedese,F., Nitti,F., Papanikas,D.G., " Experimental Results of the European HELINOISE Aeroacoustic Rotor Test in the DNW," presented at the 19th European Rotorcraft Forum, paper no. B8, September 14-16, 1993, Cernobbio, Italy

5. Splettstoesser,W.R., Junker,B., Schultz,K.J., Wagner, W. ,Weitemeier,W., Papanikas,D.G., "The HELINOISE Aeroacoustic Rotor Test in the DNW," DLR-Mitteilungen 93-09, 1993

6. Brooks,T.F., Booth, E.R., Jolly, J.R., Yeager, W.T., and Wilbur,M.L. "Reduction of Blade-vortex Interaction Noise Through Higher Harmonic Pirch Control," Journal of the American Helicopter Society, pp.86-91, Jan. 1990

7. Splettstoesser,W.R., Schultz,K.J.,Kube,R.,Brooks,T.F., Booth,E.R., Niesel,G., Streby, O., " BVI Impulsive Noise Reduction by Higher Harmonic Pitch Control: Results of a Scaled Model Rotor Experiment in the DNW," presented at the 17th European Rotorcraft Forum, paper number 91-61, September 24-26, 1991, Berlin, Germany

8. Brooks, T.F., Booth, E.R., " The Effects of Higher Harmonic Control on Blade-Vortex Interaction Noise and Vibration," JAHS, pp. 45-56, July, 1993

9. Mercker, E., and Pengel, K., " Flow Visualization of Helicopter Blade Tip Vortices," presented at the 18th European Rotorcraft Forum, paper number 26, September 15-18, 1992, Avignon, France

10. Yu, Y. H., Tung C., Gallman, J., Splettstoesser W.R., Schultz, K.J., van der Wall, B., Spiegel P., Rahier, G., Michea B., Costes, M., " Aerodynamics and Acoustics of Rotor Blade-Vortex Interactions: Analysis Capability and its Validation," AIAA 93-4332, presented at the 15th AIAA Aeroacoustics Conference, October 25-27, 1993, Long Beach, CA

11. Beaumier,P., Demargne A.,Prieur, J., Rahier,G., Spiegel,P., Kube,R., van der Wall, B.G., Schultz,K.J., Splettstoesser,Wolf, Tung C., Gallman J., Yu, Y.H., Brooks T.F., Burley C.L., and Boyd D.D., "Aerodynamic and Acoustic Effects of Higher Harmonic Control on Helicopter Rotor Blade-Vortex Interaction: Predictions

and Preliminary Validation." presented at the 75th AGARD Fluid Dynamics Panel Symposium on Aerodynamics and Acoustics of Rotorcraft, Berlin, Germany, 10-14 October 1994

12. Kube R., Splettstoesser W.R., Wagner W., Seelhorst U., Yu Y.H., Boutier A., Prieur J., and Mercker E., "Initial Results from the Higher Harmonic Control Aeroacoustic Rotor Test (HART) in the German-Dutch Wind Tunnel," presented at the 75th AGARD Fluid Dynamics Panel Symposium on Aerodynamics and Acoustics of Rotorcraft, Berlin, Germany, 10-14 October 1994

13. Brooks Thomas F., Booth Earl, Boyd D.D., Splettstoesser W.R., Schultz K.J., Kube Roland, Niesl Georg H., and Streby Olivier, "HHC Study in the DNW to Reduce BVI Noise - an Analysis," presented at the AHS/RAeS International Technical Specialists Meeting -Rotorcraft Acoustics and Fluid Dynamics, Philadelphia,PA, October 15-17, 1991

14. Van der Wall, B.G., "CP-ROT First Results from Pressure Instrumented BO-105 Hingeless Model Rotor Tests," presented at the 19th European Rotorcraft Forum, paper no. C-22, Cernobbio, Italy, September 1993.

15 P. J. Sevenhuijsen, "The Photonical Pure Grid Method," Optics and Lasers in Eng. 18 (1993)