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Into the Physics of Rotor Aeroacoustics - Highlights of recent European Helicopter Noise Research

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Abstract

Significant advances in understanding and controlling helicopter noise have been made in the course of several major European dedicated rotor aeroacoustics research projects over the past five, or so, years. The availability of the German Dutch Wind Tunnel (DNW), in particular, has enabled research on relatively large main rotor models (up to typically 40% full-scale). Here, the simultaneous application and use of blade-mounted absolute pressure sensors to probe into the very aeroacoustic source mechanisms, of advanced acoustic-data acquisition systems for the radiated noise, of sophisticated flow visualisation and flow measurement techniques (such as the Laser Light Sheet and the Laser Doppler Velocimetry techniques) as well as of the Projected-Grid method (a simplified Moiré technique) to study the complex interrelationship of rotor aerodynamics and blade dynamic response, has provided much insight into the physics of rotor aeroacoustics. In an effort towards controlling rotor noise, major research projects dealt with higher harmonic or individual blade control to try and affect the intricate interaction processes of blades and shed vortices causing intense impulsive noise. Much of the data acquired served as benchmark information to advance theoretical approaches to predict rotor noise for conditions of moderate tip speeds on the basis of linearised potential flow methods or of Euler methods in combination with the „acoustic analogy approach", and for conditions of high tip speeds on the basis of Computational Fluid Dynamics and Kirchhoff approaches.

This paper discusses several major European helicopter aeroacoustics research projects (among others the European-Union-initiated research projects HELINOISE and HELISHAPE, and the joint European-US research project HART) and presents highlights of results to indicate recent progress made in the above areas and how the findings help to provide guidance towards the ultimate objective - the quiet helicopter.

1. Introduction

1.1 The Challenge

European helicopter industry has to compete on the world market. New helicopters can only sell if they are better performers, consume less fuel, are operationally more reliable and environmentally more friendly than their predecessors. Environmental friendliness means less gaseous emissions and less noise. Exterior noise, in particular, has become an important sales argument in densely populated areas and has thus evolved into a major design parameter for the next generation of quieter rotorcraft.

Theoretical and experimental research must provide the necessary tools for helicopter aviation (manufacturers and operators alike) to achieve the ambitious goals of designing quiet helicopters and of operating them with minimum noise. To this end, manufacturers need reliable prediction schemes for the noise radiation of helicopters and guidance towards the design of inherently quiet rotor systems. Operators need to understand the complex relationship of flight-operational procedures and noise emission to enable them to „fly neighbourly“.

Helicopter industries, research establishments and universities in Europe - often within joint efforts - have accordingly endeavoured upon a number of major research projects of both experimental and theoretical nature to further the understanding of the complex acoustics of helicopters in all its facets. During the past five to ten years, several multinational research efforts involving wind tunnel and flight tests were executed in an effort to try and probe into the physics of rotor aeroacoustics - impulsive phenomena in particular - and to devise means to influence and control helicopter noise at the very source or by operational means.

In this paper, highlights and representative results from such dedicated European research programmes dealing with the physics and theory of rotor aeroacoustics will be presented.

1.2 European Helicopters

The three major European helicopter manufacturers - *Agusta, Eurocopter* and *Westland* - produce about a dozen different types of (civil) helicopters. Fig. 1.1 shows the current European product portfolio including some new or derived versions to soon enter the market. The current products encompass the weight (actually take-off mass) range from the medium-weight Eurocopter single-engine AS350 (2100 kg) up to the (civil version of the) three-engine EH 101, a joint venture of Agusta and Westland, with a take-off mass of 14600 kg. Most of these helicopters feature conventional (i.e. unshrouded) tail rotors with the exception of the Eurocopter AS365 („Dauphin“). New developments at the lower-weight category, such as the Eurocopter single-engine EC 120 (1550 kg) and at the higher-weight category, such as the Agusta/Eurocopter twin-engine NH 90 with a take-off mass of 9100 kg complement the product portfolio. Another new development, the Eurocopter twin-engine EC 135 (2.5 tons) will feature a shrouded tail rotor („Fenestron“) largely for acoustic reasons.

In all new designs, or in derived versions of existing types, novel acoustics technology will be an integral part. Advanced rotor designs, new expanded rotor-operational features (such as variable rotor speed), special noise- and vibration-reducing blade control mechanisms or the employment of „Fenestron“-tail rotor configurations will play an important role in such new developments, as will improved interior noise treatments (and vibration control) for the benefit of the passengers and crew.

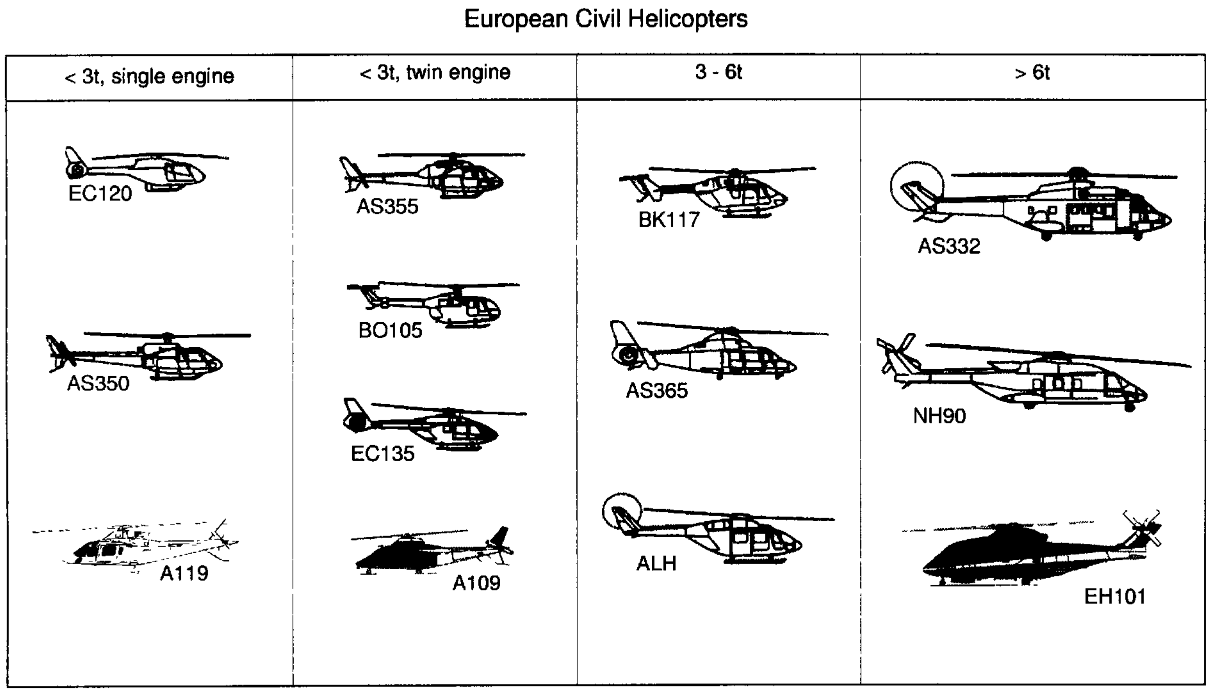

Fig. 1.1 European Civil Helicopters

1.3 Research Approaches

The European helicopter acoustics specific research programmes served three purposes, namely

- to significantly improve the knowledge about the physics (more specifically the aeroacoustics) of rotor noise,
- to provide reliable acoustic benchmark data for validating and improving theoretical prediction schemes, and lastly
- to develop and validate technically feasible noise reduction measures.

On the experimental side, corresponding efforts were greatly helped by the availability of excellent aeroacoustics research facilities such as special wind tunnels - the German Dutch Wind Tunnel, DNW, in particular - and by technically highly evolved rotor test facilities as well as by creative test approaches. Significant advances were made in the understanding of rotor aerodynamics and dynamics by novel experimental tools. For example, the *Laser Light Sheet* and the *Laser Doppler Velocimetry* techniques allowed to trace vortex paths and to clarify vortex characteristics especially at conditions of blade vortex interaction, the *„Projected Grid"-method,* a variation of the Moiré technique, served to study blade dynamic behaviour, and the *Particle Image Velocimetry* technique will soon enable to investigate relatively large areas of vorticity near rotating blades. Invaluable information was obtained on the aeroacoustics of both blade vortex interaction and high speed impulsive noise by simultaneously measuring *unsteady blade pressures directly on the rotating blades* and the ensuing *acoustic radiation* to reveal their intricate causal interrelation. In addition *flight tests to validate wind tunnel experimental results* were initiated. It should be noted in passing that the resulting information also greatly helped to answer many questions in the context of helicopter noise certification.

On the theoretical side, the accuracy of forecasting rotor noise was significantly advanced, specifically that of predicting *blade vortex interaction (BVI) noise* under conditions of moderate speed descent by means of linear potential or acceleration potential flow methods in combination with 'Ffowcs Williams and Hawkings' (FWH) use of Lighthill's acoustic analogy approach or of predicting *high speed (HS) impulsive noise* for conditions of hover and fast forward flight by means of full potential or Euler methods to capture the compressibility effects combined with the FWH-approach or the Kirchhoff method.

1.4 Content of Paper

In *Section 2* a brief account of the content and objectives of several major European rotor acoustics research projects will be given and theoretical approaches to predict rotor noise as taken by research establishments, industries and universities be discussed in general terms. *Section 3* presents selected highlights of these projects and efforts in greater detail. Section 4 will illustrate how the findings of these rotor aeroacoustics research help to provide guidance towards the ultimate objective - the acoustically non-intrusive helicopter.

2. European Research Programmes and their Objectives - Survey

2.1 Experimental Projects

Dating back to the early eighties, helicopter rotor aeroacoustics research took a major surge, none in the least by the availability of the German Dutch Wind Tunnel (DNW) in the Netherlands. This tunnel for the first time allowed the conduct of experiments with large scale (main) rotor models (up to 40% full scale) under realistically simulated flight conditions in an acoustically non-reflective (> 80 Hz) environment.

<u>*2.1.1 Early Projects (< 1989)*</u>

Already in 1982 within a joint US-Army/DLR-research project [1,2,3] a 14%-model of the AH-1/Operational Loads Survey (OLS) rotor was tested in the DNW for its impulsive noise characteristics. Although providing acoustic radiation data only for the upstream/downward regime, the tests nevertheless provided important initial information on the relationship of unsteady blade surface pressures and acoustics, the latter being of great interest in conjunction with earlier flight tests by the US-Army, since an assessment of model scale wind tunnel and full scale flight test acoustic radiation data agreement was possible. Several rotor acoustics projects in the DNW without European participation followed in the mid-to-late eighties, such as the Boeing 360 20%-scale model test [4,5], the small-scale HARP-rotor test by McDonnell Douglas [6], and the 17.5%-scale UH-60A test by Sikorsky [7,8].

A significant advancement in experimental versatility came with the new DLR-ROTEST [9] drive in 1986 for investigating the aeroacoustics of rotors in the open-test section of the DNW. This drive system allowed the operation of model-scale main rotors up to (and even slightly beyond) a diameter of 4 m still within the „healthy", low-turbulence core flow of the tunnel. More importantly, the ROTEST-drive, being supported by a rear sting mount without obstructing the regime under the rotor, enabled acoustic radiation field surveys below, as well as upstream and downstream of the rotor over an extended area. Thus, in the late eighties, a number of extensive rotor aeroacoustics research programmes was initiated which took full advantage of these new experimental capabilities, such as DLR-NASA tests on BVI noise directivity, source localization and broadband noise [10, 11, 12, 13]. Several of these programmes were exclusively executed by European research scientists within the framework of the BRITE-EURAM aeronautics initiative of the European Union (EU), others bilaterally involving European research establishments, and still others in collaboration with US-research entities.

Table 2.1 puts these projects in a time frame of 10 years with their Acronyms (where pertinent), the participants and the primary objectives, to be discussed in more detail below.

Table 2.1 European Rotor Acoustics Research Projects - Ten Years Time Frame

HHC Rotor Aeroacoustics (NASA, Aerospatiale, DLR) - ***1989/90*** – Higher Harmonic Blade Control; Source and Radiation Mechanisms
HELINOISE (EU-Project with 8 European Partners) - ***1990/93*** – Conventional Rotor (BO 105) Blade Surface Pressures and Radiation
IBC (ECD, ZF-Luftfahrttechnik, DLR, NASA) - ***1990/93*** – Full-scale BO 105 Main Rotor Tests => Acoustic Radiation under IBC Conditions
HELISHAPE (EU-Project with 16 European Partners) - ***1993/96*** – Advanced Rotor (French 7A and 7AD) Blade Surface Pressures and Radiation
HART (MoU US-Army, NASA, DLR, ONERA, DNW) - ***1990/95*** – Conventional Rotor (BO 105) Blade Surface Pressures + Radiation under HHC
ERATO (ONERA, DLR) - ***1992/97*** – Quiet Helicopter Concept, New-design Model Rotor ⇒ 6 dB Noise Reduction
FLYVAL (DLR) - ***1995/98*** – Validation of Aeroacoustics Wind Tunnel Test Results through BO 105 Flight Tests
HELIFLOW (EU-Project with 11 European Partners) - ***1996/99*** – Interactional Aerodynamics and Aeroacoustics (Rotor/Rotor- and Rotor/Fuselage)
RODOS (MoU US-Army, NASA, DLR, ONERA, DNW) - ***1998/99*** – Rotor Downwash and Wake Geometry Measurements (free wake code improvement)

2.1.2 Recent Projects (> 1989)

A first of such extensive European rotor research programmes in the time frame 1990 through 1993 was initiated by the European Union (EU) under the acronym **HELINOISE.** It involved 8 European Partners from industry, research establishments and universities. A 40% geometrically and dynamically scaled model of the MBB (now Eurocopter Deutschland, ECD) BO 105 helicopter 4-blade main rotor was tested in the open-jet anechoic test section of the DNW. One of the blades was equipped with a large number of absolute pressure sensors. The primary objectives of the experimental part of the study were to (a) improve the physical understanding of the most intrusive impulsive noise sources by correlating unsteady blade pressure and acoustic characteristics and to (b) provide an extensive airload and acoustic data base for code validation purposes. Since long it was recognised that information on blade dynamics and rotor wake characteristics was crucial in understanding blade vortex interaction (BVI) phenomena and first relevant data on blade-vortex separation distances during BVI were gathered. Regions of impulsive loading on the rotor disk due to BVI at descent conditions and of supersonic flow at high advancing tip speeds were identified and related to the ensuing acoustic radiation.

A subsequent EU-initiated research project - undertaken from 1993 to 1996 - with meanwhile 16 European partners under the acronym **HELISHAPE** featured a highly instrumented Eurocopter France, ECF, 4-blade model rotor. This rotor employed newly designed, state of the art blades with two exchangeable blade tips. Taking full advantage of the experience gathered in the preceding HELINOSE tests, the new multination project aimed at evaluating noise reduction techniques, conceptually by variation of rotor speed, dedicated tip shapes and advanced airfoils, as well as operationally by identifying low-noise, BVI-minimising, descent procedures. Fulfilling an important objective, the data were widely used to validate some of the partners' advanced aerodynamic and acoustic codes. Again, detailed blade surface unsteady pressure data were determined simultaneously with the acoustic radiation data. Valuable information on tip vortex trajectories and blade-vortex separation distances during BVI was gathered by means of the Laser Light Sheet technique. All data served to compare the aeroacoustic characteristics of the standard rectangular tip blade with the advanced non-rectangular tip blade.

Already in the late eighties, a first experimental study - again in the DNW and using the BO 105 40%-scaled model rotor within a trilateral DLR/NASA/Aerospatiale research project - had shed first light on the physics of higher harmonic control (HHC) of rotor blades as it affects both the vibration and the acoustic characteristics of a rotor. Originally, the idea of harmonically controlling the blade pitch (in essence by superposing a sinusoidal „higher harmonic“ motion upon the once-per-revolution cyclic pitch motion by means of actuators in the <u>non-rotating</u> system under the swash plate) was developed to reduce rotor vibration only. It was recognised, however, that such a harmonic blade control might also offer benefits for noise reduction by affecting the strength and the very generation and shedding processes of vortices, as well as their trajectories and their final interaction with the blades. Accordingly, already in this first study both vibration and acoustics were investigated to reveal the potential of this technique, if only with a severe drawback: the benefits of vibration reduction and acoustics reduction seemed to be mutually exclusive. Clearly, a more thorough investigation was called for. Based on the experience of this first trilateral HHC-Aeroacoustics study and of the HELINOISE investigations, a new - transatlantic co-operative - rotor acoustics project was initiated under the acronym **HART** (**H**igher harmonic control **A**eroacoustic **R**otor **T**est) involving two European partners DLR and ONERA and two American partners, the US-Army and NASA. The idea was to combine the HHC-control apparatus with the instrumented BO 105 40%-scaled model rotor to investigate the unsteady pressure characteristics on the blades and the ensuing acoustic radiation under conditions of HHC. The highly successful HART project, occurring in the time frame 1990 to 1995, was probably the most comprehensive rotor aeroacoustic research project to date conducted in the DNW. In the end the project yielded a unique set of acoustic, aerodynamic, dynamic-blade-response, performance and rotor wake data, its primary objectives being to improve the physical understanding and the mathematical modelling of the effects of the HHC technique on BVI impulsive noise and vibration.

While the advantages (and limitations) of the HHC method became more fully understood, interest turned to **Individual Blade Control (IBC)** as a more direct means to control blade aerodynamics and its dynamics response and to tailor an individual blade's airload and motion to optimise its effect on noise and vibration. The obvious shortcomings of HHC, where the pitch angle of one blade cannot be changed without changing the pitch of the other blades, are overcome by introducing actuators in the rotating system. Accounting for the dynamic behaviour of a given blade the input control function (of whatever complex nature) can be optimised to arrive at the desired pitch function at the blade tip. European researchers from industry and research establishments were involved in a substantial acoustics and vibration study on IBC control and effects that took place in 1993 at the NASA Ames 40 by 80 ft. wind tunnel using a full scale BO 105 rotor.

To start out with aerodynamically and acoustically more optimum blades, rather than trying to obtain needed benefits by active rotor control (such as HHC or IBC), an ongoing bilateral European R&D-project between ONERA and DLR (1992 - 1998), entitled **ERATO** (**E**tude d'un **R**otor **A**eroacoustique **T**echnologiquement **O**ptimale), endeavours to design a rotor significantly quieter than a reference state-of-the art existing rotor and to validate the expected benefits through scaled-model tests in the DNW and in the French S1 Modane Wind tunnel. The rotor design, featuring a new blade geometry (airfoil, planform and twist distribution), was based on thorough computational aeroacoustic prediction efforts where relevant design and operational parameters were systematically varied to arrive at a noisewise optimum geometry.

While wind tunnel experiments allow testing over a wide parameter range without great operational risk, (full-scale) flight tests of inherently restricted parametric variation range are none-the-less of great importance to validate model test results. A dedicated wind-tunnel/flight-test validation programme under the term **FLYVAL** was initiated by DLR in 1995 employing DLR's BO 105 helicopter to check on previous DNW test results, where geometrically and dynamically scaled BO-105 model rotors had been used. Unsteady blade pressure data (rather than acoustic signatures below the rotor) were compared for a wide variety of test (flight) conditions including moderate to high speed level flight and moderate speed descent to reveal any model/full-scale discrepancies. To this end one of the flight test helicopter's rotor blade carried a small number of absolute pressure sensors at locations corresponding to those used in the HELINOISE and the HART model tests. Currently a major follow-on flight test programme to resolve some of the open questions is in the final preparation stage.

Recently (in 1996) another EU-sponsored helicopter rotor noise research project under the acronym **HELIFLOW** began with 11 European partners to study the aerodynamics and aeroacoustics of main-rotor/tail-rotor and rotor/fuselage interactions both experimentally and theoretically. For the experiments in the DNW, the BO 105 40%-scaled main and tail rotors both carry absolute pressure sensors; this will - among other objectives - help to investigate the noise source mechanisms of the tail rotor when impinged upon by the main rotor wake, or by the wakes shed from the hub and the fuselage under a variety of flight conditions.

Finally, the successful HART project will be continued. Plans call for the investigation of the unsteady rotor downwash and BVI geometry in an effort to obtain much needed information on the behaviour of the main rotor wake, on the blade response and on blade airloads. The primary objective of this effort is to improve and validate the prediction capability for the free wake (especially tip vortex development). The new effort runs under the acronym **RODOS** (**RO**tor **DO**wnwash **S**tructure programme) to be started in 1998.

2.2 Theoretical Approaches

Although all these projects involved substantial experimental efforts to study the physics of rotor noise, they nevertheless were also crucial in advancing theory and prediction capabilities. Indeed, in the course of the past five to ten years, or so, significant progress was achieved in rotor aeroacoustics theory both in Europe and in the United States of America often based on the benchmark data obtained in these projects.

The noise radiated by a rotor blade is significantly affected by the highly complex flow-field it encounters during operation being characterised by three-dimensionality, unsteadiness, transonic flow regions and viscous effects. In forward flight, unsteadiness is introduced by the cyclic variation of the free stream velocities relative to the (rotating and advancing/retreating) blades and the cyclic modulation of blade pitch, flapping and lead/lag motions. Under conditions of moderate-speed descent a blade may also encounter temporally varying flow regions when it passes through its own wake and the wakes of preceding blades leading to the phenomenon of blade vortex interaction impulsive noise. During high speed forward flight conditions, flow near the blade tip on the *advancing* blade becomes transonic with supersonic pockets appearing near the blade tip leading eventually to the phenomenon of high speed compressibility noise. If speeds increase even further the rotor is encompassed by a shock field which streams away from the rotor, a phenomenon known as shock delocalisation which is perceived in the acoustic farfield as high speed impulsive noise. Under such flight conditions the cyclically increased pitch on the *retreating* blade may also generate regions of dynamic stall with ensuing flow-reversal and flow-separation at the blade root. For a realistic simulation of rotor flows these unsteady aerodynamic effects must be modelled.

Several quite successful approaches have been developed in the course of time to predict helicopter rotor noise, known under the designations *Lighthill's acoustic analogy* (aeroacoustic source terms), *Kirchhoff-fomulations* (hybrid Computational Fluid Dynamics, CFD, and Kirchhoff methods), and *Computational Aeroacoustics* (use of aerodynamic methods for direct noise calculations). A general schematic of rotor noise prediction approaches appears in Fig. 2.1.

In order to predict rotor noise, say in terms of acoustic pressure time histories at an observer point, noise may be broken down into three source-types occurring on a rotor, namely thickness noise, loading noise and compressibility noise.

Hence, the acoustic analogy approach utilises three corresponding aerodynamic source terms, i.e. the linear thickness noise term (with the characteristics of an aerodynamic monopole), the linear loading noise term (with the characteristics of an aerodynamic dipole) and the non- linear compressibility noise term (with the characteristics of an aerodynamic quadrupole) as inputs into appropriate acoustic codes, such as the Ffowcs Williams and Hawkings ("FWH") formulation [14, 15] which in turn is based on the classical Lighthill formulation of aerodynamic noise [16].

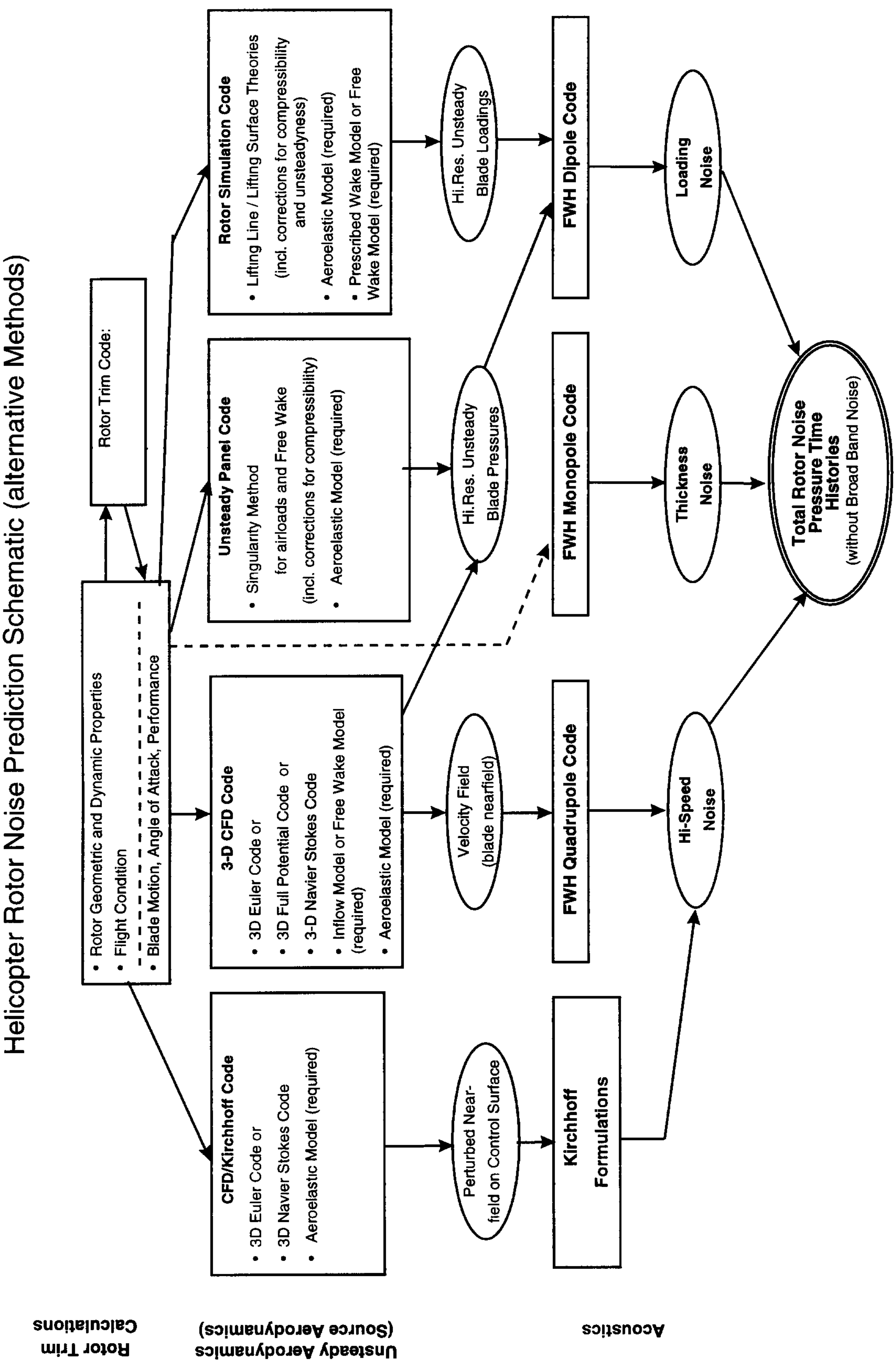

Fig. 2.1 Helicopter Rotor Noise Prediction Schematic (alternative Methods)

The **monopole source term** can be computed solely from information on blade geometry and kinematics, the latter depending on rotor operational conditions. The **dipole source term** can be determined in several ways. One approach is based on inviscid potential flow methods, suchas *lifting line* or *lifting surface theory*, or *unsteady panel methods* based on singularity theory to yield, respectively, high-resolution unsteady blade loadings or high resolution unsteady blade pressures. Another approach to determine the acoustic dipole source term is based on solutions of *Euler equations* which again provide high resolution blade pressure information. The characteristics of the inviscid potential flow methods are as follows:

- In lifting line theory (see e.g. [17]) the lift is considered to be generated by a single ('bound') vortex filament at the blade quarter chord along the blade span. Pressure equalisation at the blade root and tip generates root and tip vortices. Blade rotation and forward motion cause these 'wake' vortices to follow a complicated helical path to constitute the 'wake'. Often this vortex wake is taken as time invariant („prescribed wake"), although it is presently fully recognised that a free wake model must be included into the lifting line code, as must also the elastic properties of the blade to arrive at better simulations. The output of the calculation is only the lift distribution over the blade span as input into the acoustic codes, without regard to the details of blade planform, tip shape, profile etc.
- If the lift variation over the chord is of importance, the lifting surface method (see e.g. [18]) accounts for it with a distribution of lifting lines over the blade chord. The concept allows for both including or neglecting blade thickness as the distribution is spread over a blade chord. Thus, non-rectangular blade planforms with twist and blade tip modifications can be simulated and the ensuing pressure data be used as input into the acoustic codes.
- Unsteady panel methods (see e.g. [19]) permit the modelling of the aerodynamics of *arbitrarily shaped* bodies. In essence all geometric parameters of a real blade (profile geometry, planform, twist, tip shape etc.) can now be accounted for. The calculations yield the pressure and velocity distribution on the upper and lower blade surfaces. Accordingly, a more realistic simulation of blade geometry and correspondingly more detailed aerodynamic information is available as input for the acoustic codes.
- The alternative method to arrive at the dipole source term is to compute the acoustic nearfield blade pressures by means of an Euler solver. Blade loading is evaluated by integrating the pressure over the surface grid of the blade used for the aerodynamic computations (see e.g. [20]). This method inherently accounts for the blade's geometrical details.

Linearised potential flow methods to compute the dipole source term need only moderate computation time and are well suited for application in prediction schemes of rotor noise for blade tip speeds well below those where major supersonic flow regions on the blade would appear, i.e. at low to moderate forward speeds. Their inherent drawback is their inability to account for compressibility effects as needed to compute the **quadrupole source term**. At higher speeds, though, the quadrupole source term must be included, even if only in an approximated form once supersonic flow regions and shocks near the blade tip appear during forward flight (see e.g. [21])

Treatment of such non-linear effects is the domain of 'field methods' such as full potential or Euler methods [22]. If the rotor is encompassed by a shock, the quadrupole field must be accurately evaluated through appropriate volume integration procedures. This however is a very involved process.

Here, the *combination of CFD and Kirchhoff-methods* [23] represents a more appropriate and in fact more flexible technique to compute the acoustic radiation at high tip speeds for conditions of hover or level flight compared to the Euler/FWH-approach. Accordingly it is advantageous to determine the near field aerodynamics and acoustics by means of full potential or Euler/Navier-Stokes equations, accounting for all non-linear compressibility effects. The solutions are then integrated onto the Kirchhoff surface which completely surrounds the rotor at an appropriate distance. Starting from that surface around the non-linear nearfield of the rotor, computation of the subsequent acoustic propagation into the farfield requires only linear equations.

Hence, the Kirchhoff surface divides the flow region into an inner part where non-linear effects prevail (and where the flow solution is obtained by solving the Euler equations) and an outer part where linear acoustic wave propagation prevails. This combination of the Euler and Kirchhoff methods provides better agreement of measurements and prediction than the direct computation of the acoustic farfield solely by means of an Euler approach.

In summary then (a) linearized inviscid potential flow methods in combination with the acoustic analogy approach, and (b) analyses using Euler results in combination with acoustic analogy approaches are suitable for rotor noise predictions at low to moderate tip speeds. For high-tip-speed cases, including those where shock delocalisation occurs, CFD/Kirchhoff approaches may be better qualified. Here the CFD-based computationally expensive flowfield calculations are confined to the nearfield inside the Kirchhoff surface where non-linear effects prevail. Prediction of the farfield acoustic pressure field with the Kirchhoff surface representing the source surface can then be based on linear acoustic wave propagation. Several representative results relating to these various approaches will be presented in the subsequent sections of this paper.

All of the above approaches are worked on within these European joint research programmes and significant progress has been achieved. However the complete computational description of a main-rotor/tail-rotor/fuselage system both in terms of unsteady aerodynamics and acoustics is still far in the future.

3. European Research Programmes - Highlights

While in the previous section, a general overview of research projects was given, these projects will now be discussed in greater detail, presenting and highlighting major findings on the aeroacoustics of helicopter rotors. Starting approximately at the 1990 point in time, important/representative results from the European Union aeronautical research initiatives HELINOISE and HELISHAPE, from the European/US project HART, from the German/US IBC-project, from the French-German ERATO project, and from the Wind-Tunnel/Flight-Test Validation project, FLYVAL, of DLR will be presented.

3.1 The EU-Project HELINOISE

The HELINOISE project [24, 25] was the first major European research project where the radiated acoustics was simultaneously measured with the unsteady blade surface pressures. The test set up in the open test section of the DNW (Fig. 3.1) features a geometrically and dynamically 40% scaled 4-bladed hingeless model rotor of 4 m diameter with rectangular blade tips

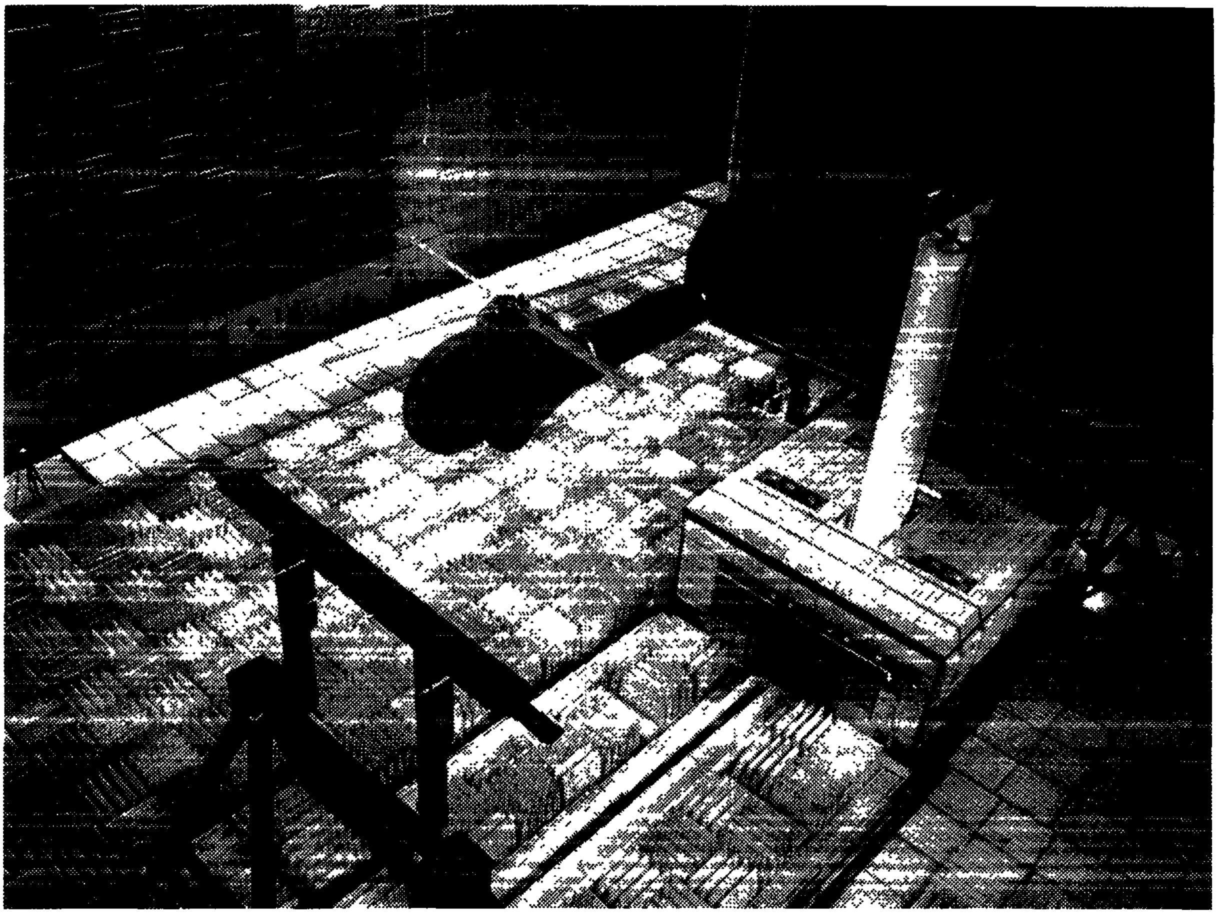

Fig. 3.1 Model helicopter rotor in the open test section of the DNW (flow from left to right)

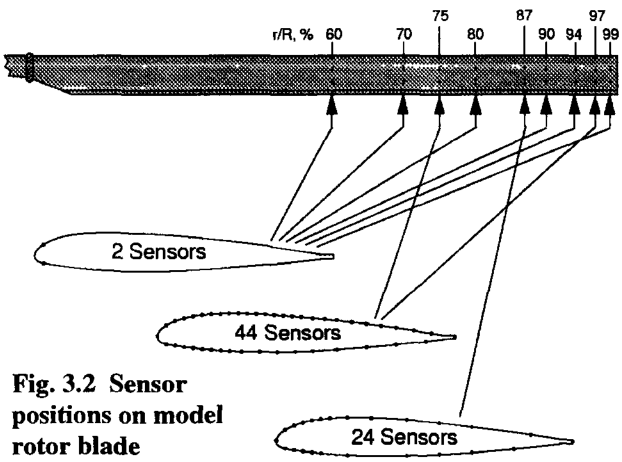

Fig. 3.2 Sensor positions on model rotor blade

and NACA 23012 airfoils of the MBB BO 105 helicopter. Detailed information on the rotor characteristics, blade geometry and dynamic properties are given in [26]. The model rotor is positioned 7 m downstream of the 6 by 8 m nozzle slightly above the tunnel centreline, to allow traversing of the microphone array below the rotor still within the core of the free jet flow. This inflow microphone array consists of 11 laterally equally spaced nose-cone protected ½-inch B&K microphones. The array traverses the measurement plane 1.15 rotor radius (R) below the hub and over a hub-relative distance of 3R in the upstream and 2R in the downstream direction; in the lateral the measurement area extends 1.35 R in both directions. Further details about the rotor assembly as such can be found in [27].

A key issue of the HELINOISE project was the acquisition of unsteady blade surface pressures. To this end, one of the rotor blades carried a combined total of 124 absolute pressure sensors (Kulites) on the upper and lower surface (Fig. 3.2). Details on the acquisition-technique for unsteady blade surface pressure and other unsteady aerodynamic data appear in [28].

A typical result of a surface pressure distribution over the rotor area (more specifically over the outer 40% radius, where sensor information near the leading edge was available) and the ensuing acoustic radiation field is shown in Fig. 3.3 for a test condition of a moderate speed (33 m/s) 6°- descent where strong BVI occurs. The BVI traces - depicting the interaction of the tip vortices with the blade in the first (advancing side) and fourth (retreating side) rotor quadrant - are clearly visible (Fig. 3.3/left). Such blade surface pressure information allows estimates of vortex core size, vortex rotational direction, vortex/blade interaction angle etc. The radiated acoustic field under the rotor (Fig. 3.3/right), characterised by local maxima under the first and fourth rotor quadrant, illustrates the close relationship with the blade surface pressure field. It is worth noting that the radiation intensity in the fourth quadrant seems less than in the first quadrant, although the pressure gradients on the blade surface - as a consequence of the BVI - are much steeper in the fourth than in the first. This is probably caused by the much lower relative tip Mach number in the fourth quadrant compared to the first quadrant.

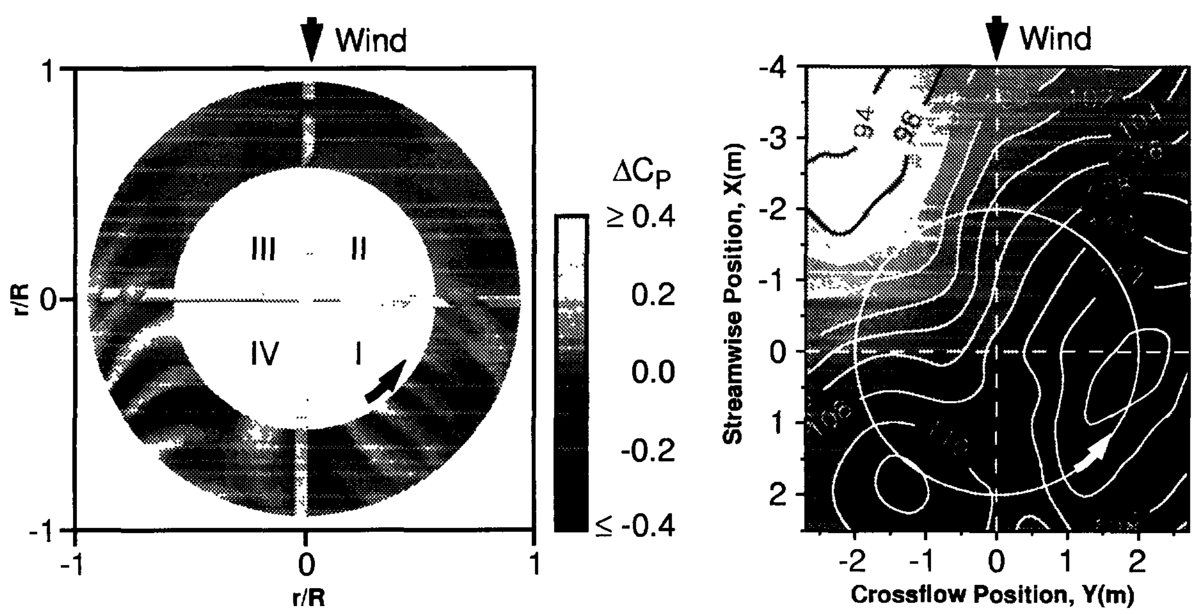

Fig. 3.3 Blade surface pressure contour plot during one rotor revolution (high-pass filtered) for several sensors near the leading edge (left); corresponding acoustic radiation in terms of sound pressure level isobars below the rotor (right) for a moderate speed descent flight condition with strong BVI

Rather than visualising the entire („global") surface pressure field over the rotor disk, traces from individual sensors reveal other important characteristics of the blade surface aerodynamics in particular detail. As an example, the (averaged) blade pressure histories on the lower blade surface at different radial (r/R) and chordwise (x/c) locations for one rotor revolution at a condition of high speed forward flight (hover Mach number $M_h = 0.640$, advance ratio $\mu = 0.347$) are shown in Fig. 3.4. It can be seen that the supersonic flow region, built up during the blade passage through the second quadrant (90° < ψ < 180°), is located at the outer span, although confined to the leading edge region.

The Laser Light Sheet (LLS) technique [29] was first successfully applied in the HELINOISE-project to visualise tip vortex sections to obtain - initially qualitative - information on vortex structure (especially the location of the vortex core centre) and quantitative information on the geometry of tip vortex segments (wake), as well as on blade vortex separation distances at locations near severe BVI.

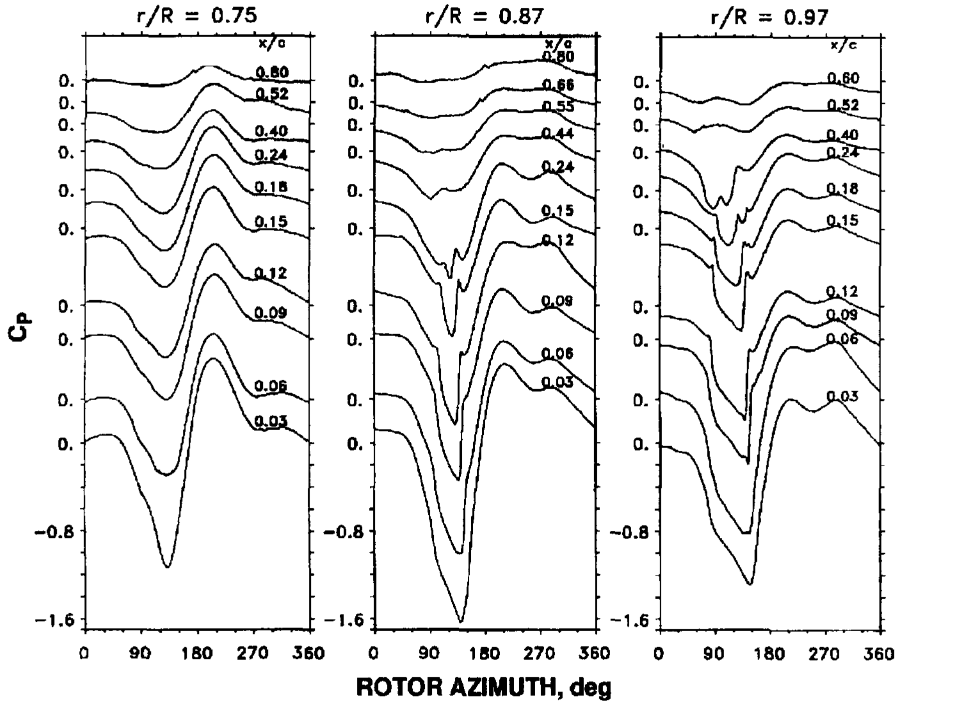

Fig. 3.4 Averaged blade pressure time histories on the lower blade surface at different radial (r/R) and chordwise (x/c) locations for a high speed level flight condition

Fig. 3.5 shows the experimental LLS set up. Here, a laser light sheet is erected normal to the rotor plane and approximately vertical to the vortices to be visualised. The laser light source was attached to the microphone traverse to allow it to be moved or rotated, depending on the requirements. Oil aerosol (smoke particles) was introduced with a „smoke-probe“ located upstream of the blade tip at that particular azimuthal rotor position where the vortex element was generated. The smoke particles were drawn into the rolling up tip vortex which subsequently convected downstream toward the light sheet. When passing the light sheet the smoke particles within the vortex cross section were illuminated such that the vortex structure, and the core region in particular, became visible (Fig. 3.6 top) to be recorded by a fast video camera.

To study blade/vortex separation distances - known to be one of the primary parameters to affect the intensity of the encounter - the vortex and the blade must be visualised simultaneously. This was achieved by synchronising a powerful stroboscopic light source (positioned next to the video-camera) with the blade azimuth to optically freeze the blade motion. A reference grid of known dimensions was placed in the plane of the light sheet (after the wind and the rotor were stopped) and recorded with the same video camera. This video-recording was superimposed onto the original video image to identify the locations of both the vortex core centre and the blade and thus to quantify their relative distance (Fig. 3.6 bottom).

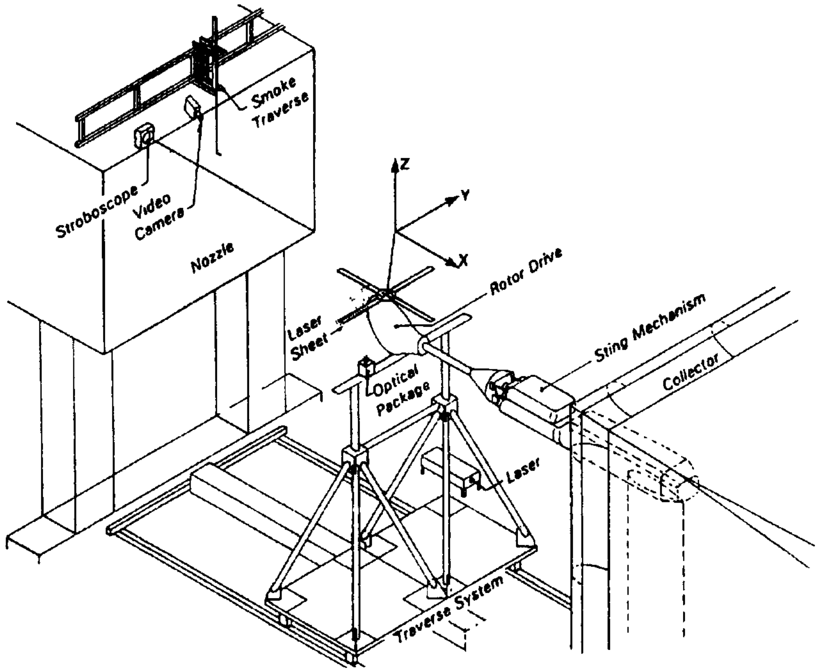

Fig. 3.5 Test set-up for flow visualisation with the Laser Light Sheet technique

To quantify vortex segments in space (in essence to determine the geometries of the vortex path, i.e. the wake) repeated measurements of the vortex core centre along a vortex line at a „frozen" vortex pattern (i.e. with the blade at a fixed azimuth angle) were conducted. The procedure is illustrated in Fig. 3.7 where individual points along selected segments of vortices (e.g. denoted vortex # 5, or vortex # 6) were determined with the blade at a fixed azimuthal angle.

A typical result is depicted in Fig. 3.8. Both the top view on the rotor tip path plane (Fig. 3.8a) and the side view (Fig. 3.8b) show a number of tip vortex segments for a typical BVI case.

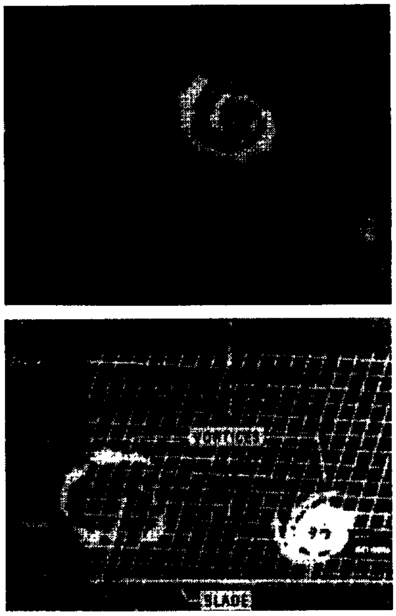

Fig. 3.6 Visualisation of blade tip vortices and quantitative determination of the blade vortex (core) separation distance by image superposition

Measured vortex segments are located above the rotor passing plane for this descent condition. Most of the separation distances are less than one blade chord length. The acoustically very important nearly parallel and closest BVI occurs at a rotor azimuth position of about $\psi = 50°$ with vortex # 6 (vortex age to correspond to $\psi = 450°$). This vortex intersects the $\Delta z/c$ - r/c plane at a slightly skewed angle. A direct blade vortex encounter is observed near the blade tip at $r/R = 0.93$. Additional interactions occur with vortices 5, 4, and 3 although at larger azimuth and intersection angles, resulting in more localised BVI sources which are acoustically less effective.

The theoretical studies on validations of computational methods which were developed or improved by the analytical research effort within the HELIONOISE project are summarised in [30]. They mostly pertained to evaluating the acoustic analogy approach where the quadrupole term was determined either on the basis of the „Schultz-approximation" [31] or on an approximation known as the „Farassat shock wave formalism" (or quadrupole decomposition) [32]. The first of these approaches „converts" the quadrupole volume integral into a surface integral by applying the so-called „momentum-thickness-concept", first introduced by Yu, Caradonna and Schmitz[21]. The other approximation employs a direct evaluation of the surface quadrupole terms; here it is shown that the volume quadrupole terms can be manipulated in such a way that they include also some surface terms and only these surface terms are then considered while neglecting the remaining volume terms. The approximations work well for tip speeds where shock delocalisation has not yet occurred. All relevant efforts were to be continued in the subsequent HELISHAPE-project.

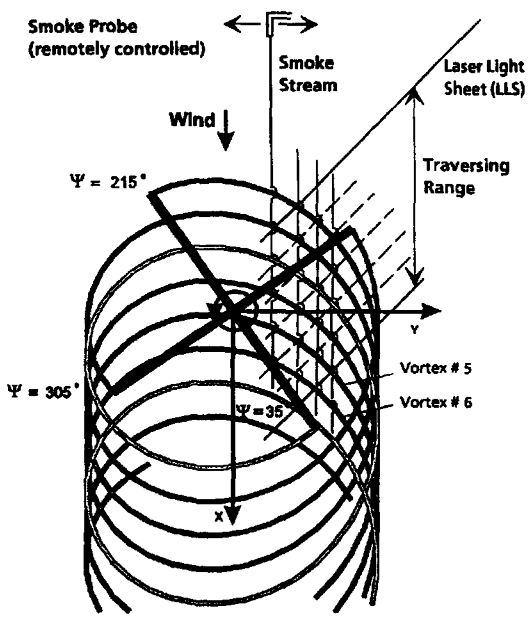

Fig. 3.7 Application of the Laser Light Sheet Technique

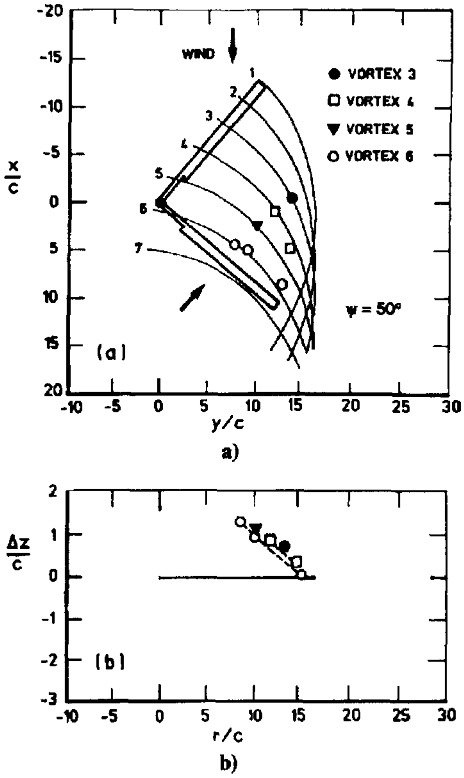

Fig. 3.8 Measured vortex section for moderate speed descent: (a) plan view comparing measurement and (prescribed) wake prediction for blade fixed at 50° azimuth, (b) side view showing measured separation distances

3.2 The EU-Project HELISHAPE

The project HELISHAPE [33, 34] was a direct follow-on to the HELINOISE project. The work was divided into several tasks, four of which related to the improvement of aerodynamic and acoustic simulation codes, one pertained to an industrial study on the potential and marketability of future quiet helicopters and one major task of experimental nature involved a comprehensive wind tunnel study in the DNW on blade aeroacoustics, blade aerodynamics, blade dynamics and unsteady flow features for two French blade designs on a fully articulated rotor. One of these blades (termed 7A) featured a rectangular tip, the other (termed 7AD1) a tip of parabolic/anhedral swept-back shape (Fig. 3.9). In particular, the potential noise reduction benefits of the blade with the advanced tip shape vs. the conventional were to be evaluated, if only in a preliminary manner. The rotor blades themselves were formed of ONERA OA209 and OA213 airfoils. The 4.2 m diam., fully articulated, 4-blade model rotor was equipped with 118 absolute pressure sensors (distributed over all four blades) to measure unsteady blade surface pressures and 28 strain gauges to measure blade flapping, in-plane and torsional moments and deflections. A photograph of the test set-up in the DNW appears in Fig. 3.10.

Ambitious goals were set within the theoretical HELISHAPE-project efforts: 3-D Euler codes for the description of multiblade hovering rotors were to be further developed, a common 3-D

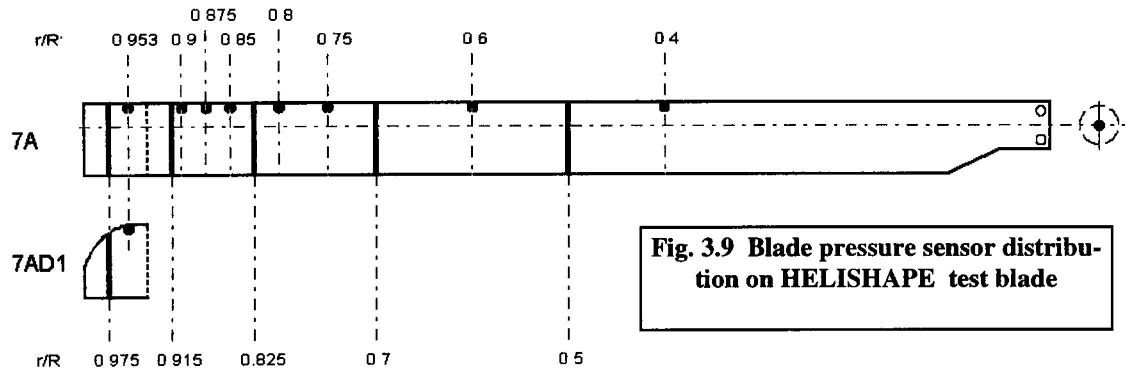

Fig. 3.9 Blade pressure sensor distribution on HELISHAPE test blade

full potential code was to be created for the analytical simulation of the entire flight regime of the helicopter, and different existing boundary element methods for the description of free wake effects were to be improved. Moreover, the acoustic analogy method, the Kirchhoff approach and computational aeroacoustics procedures were to be tested against the experimental evidence.

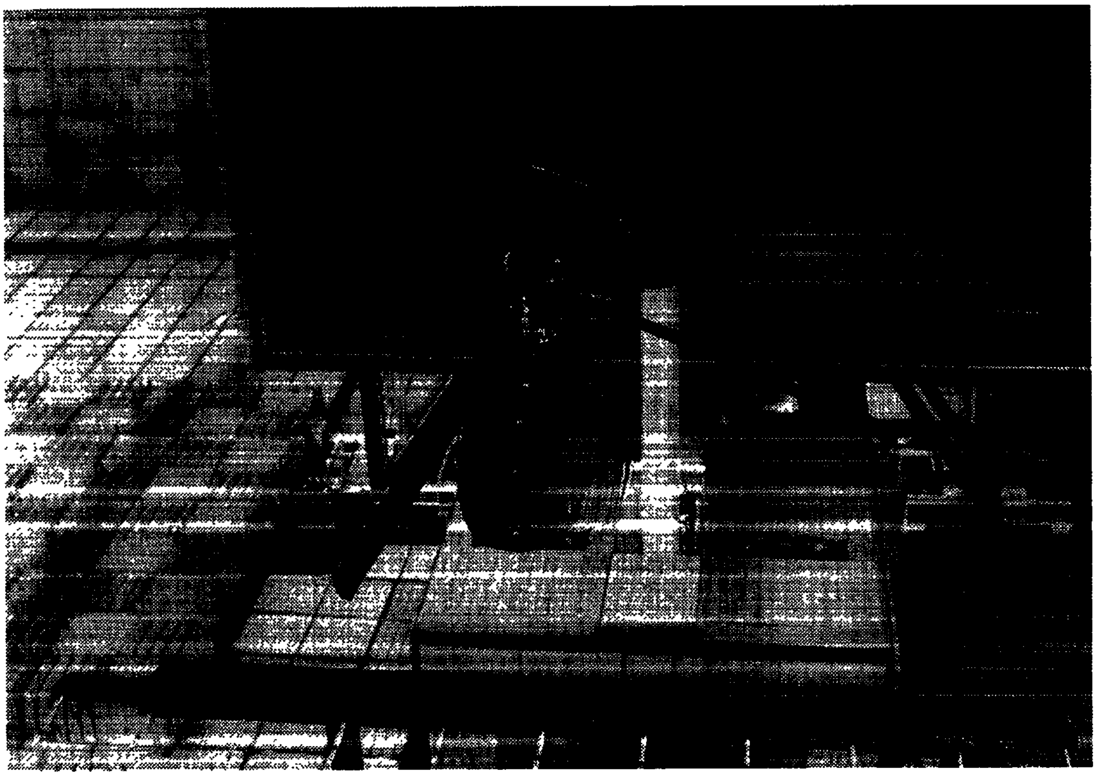

Fig. 3.10 Test set-up in the DNW with the 7AD1 model rotor in the HELISHAPE tests

A number of noteworthy experimental results were achieved. The basic test set-up was rather similar to the HELINOISE set-up, although an additional stationary microphone was mounted on the DNW-nozzle rim in order to measure high speed impulsive noise radiation, known to exhibit an upstream/rotor in-plane directivity peak. Fig. 3.11 compares the acoustic pressure time histories (PTHs) for one rotor revolution of the 7A and the 7AD1 rotor under conditions of level flight at various speeds at that microphone position. At relatively low (tunnel flow) speeds (35 m/s) the PTHs are rather similar, whereas with increasing flow speed from 61 m/s and towards 76 m/s the curved tip shape reveals its benefits. Distinctly lower negative peaks are observed for the 7AD1 rotor at speeds where compressibility effects become important.

Even under hover conditions the 7AD1 rotor shows better acoustic performance. Although at low thrust settings (actually thrust coefficient C_T) the fundamental blade passage harmonic amplitudes for both rotors were found nearly identical, at higher thrusts these amplitudes are clearly reduced for the 7AD1 rotor. Fig. 3.12 illustrates the effect of thrust increase on the A-weighted (mid-frequency emphasis) noise radiated in the direction of the advancing blade (towards the DNW nozzle microphone). For all thrust settings, the 7AD1 rotor shows generally reduced noise levels. Attention should be drawn to the fact that in wind tunnel testing, even in open-jet wind tunnels such as the DNW, a certain amount of flow recirculation occurs in the test area, to probably affect the aeroacoustics of a rotor model rotor in hover.

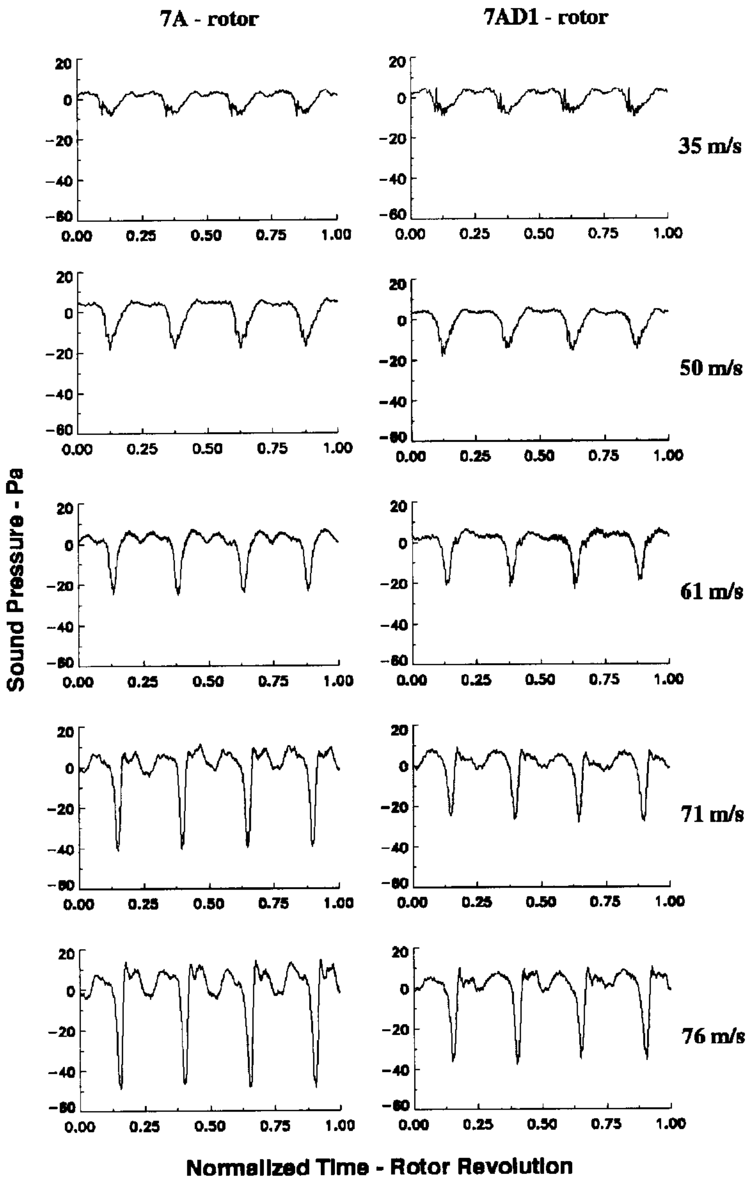

Fig. 3.11 Comparison of 7A and 7AD1in plane noise signatures in level flight for different flight speeds

The difference is less pronounced at conditions of moderate speed descent where strong BVI occurs. Here at identical operational conditions, the 7AD1 rotor is found to be only 1 - 2 dB less noisy. Evidently, the tip shape does not seem to have very much effect on the vortex path and the interaction processes are rather similar (in terms of, say, separation distance and vortex strength). This is supported by the features of the unsteady blade surface pressure field on the rotor which show little difference (Fig. 3.13).

On the other hand, under conditions of high speed flight at an advancing tip Mach number of 0.835, there is a striking difference in the chordwise blade pressure (in terms of the pressure coefficient C_p) distribution for the 7A and the 7AD1 rotors. As shown in Fig. 3.14, for a radial station of r/R = 0.975, i.e. very close to the tip) extended supersonic flow regions and shock formations are visible on the advancing side on the rotor plane between 45° and 135° azimuth for the 7A rotor. In contrast, the supersonic flow region has nearly vanished for the 7AD1 rotor.

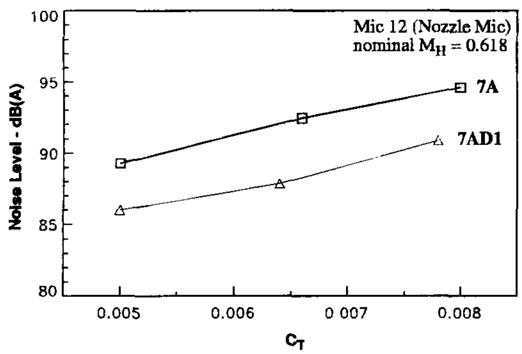

Fig. 3.12 Comparison of in-plane A-weighted levels for 7A and 7AD1rotor at hover as function of thrust setting

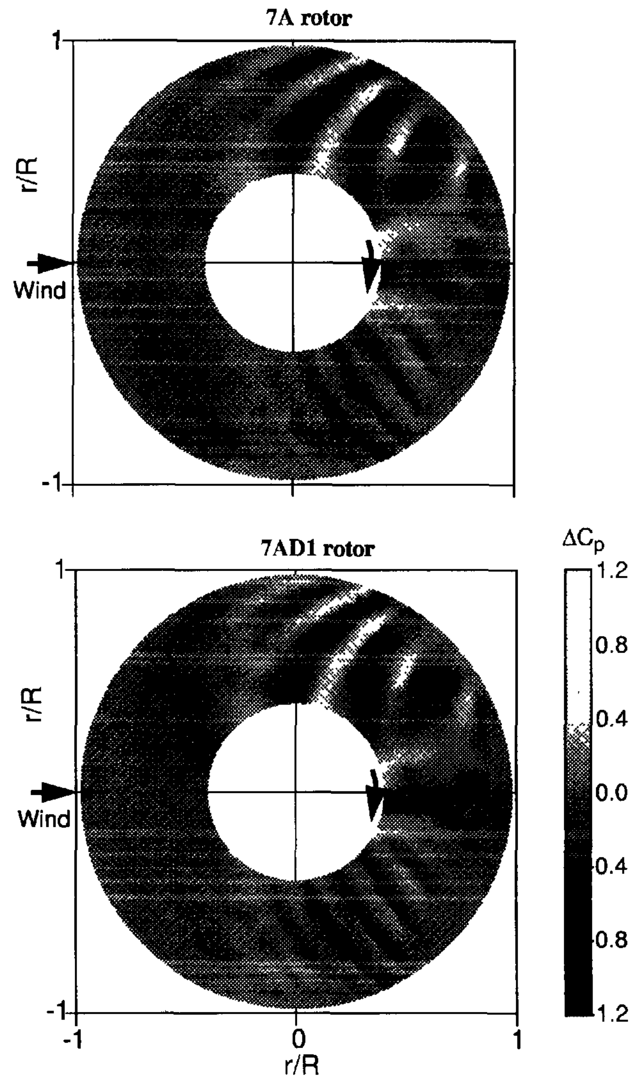

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Fig. 3.13 Comparison of azimuthal /radial differential pressure distribution for the 7A and the 7AD1 rotor at moderate speed descent

The Laser Light Sheet experiments (using the same set-up as in the HELINOISE tests) confirm the general similarity of the 7A and the 7AD1 rotor under conditions of moderate speed descent where strong BVI occurs. Fig. 3.15 shows the results for both rotors for a descent angle of 6°. Obviously the tip vortex segments for the 7A and the 7AD1 rotors are very close together. At the selected azimuthal rotor position of 55° the measured vortex segments are above the rotor. An extrapolation of the vortex path in the tip direction indicates an interaction in the outer blade span region.

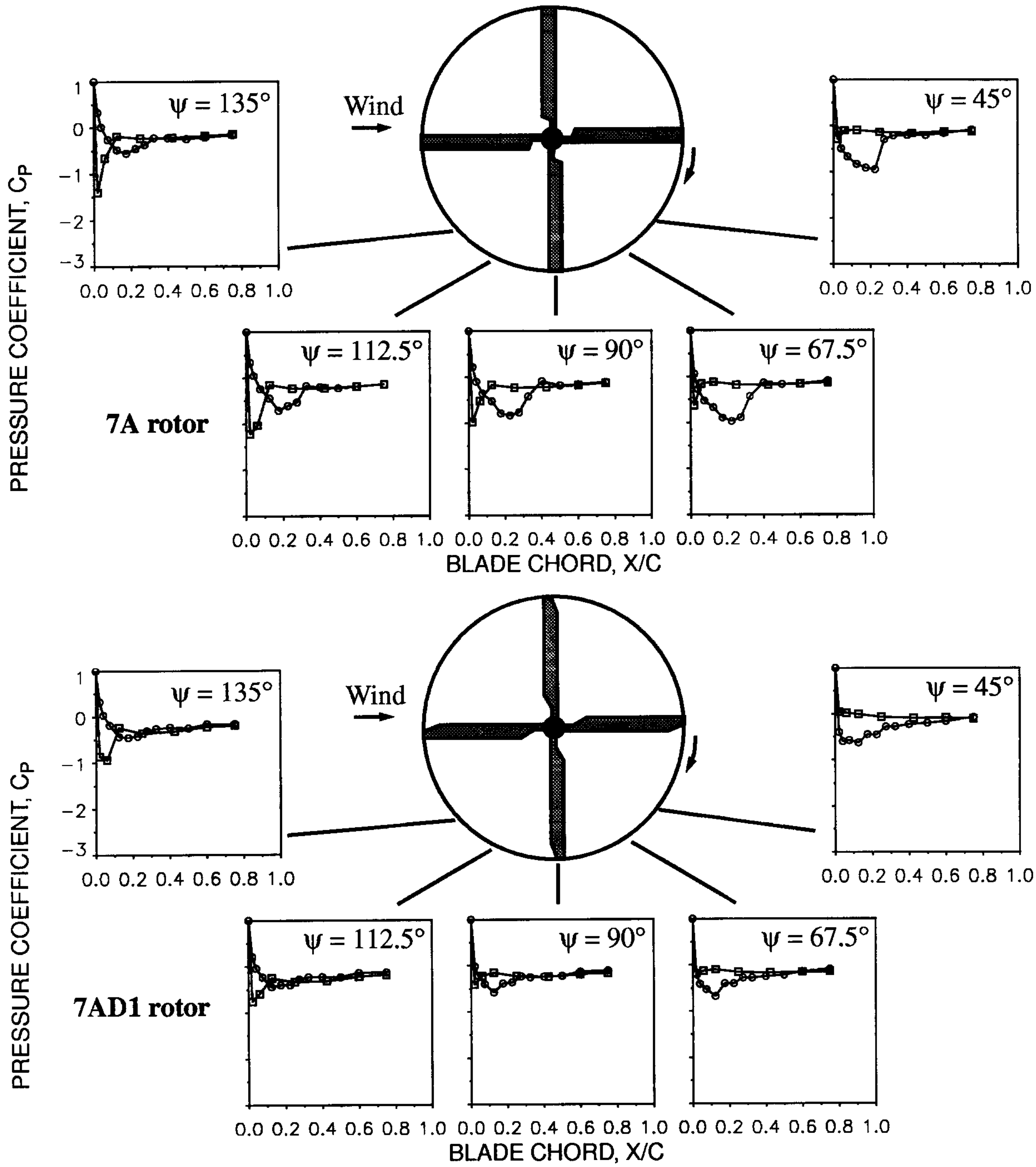


Fig. 3.14 Typical chordwise blade pressure distributions at various blade azimuth locations for high speed flight at blade position r/R = 0.75

Several significant improvements in rotor aeroacoustics theory were achieved in the HELISHAPE effort.

Regarding blade aerodynamics, the blade instrumentation with absolute pressure sensors on the 7A and 7AD1 rotors allowed a direct comparison of theoretical predictions of the pressure coefficient C_p with the measured values. The C_p-distribution across several chord-sections at

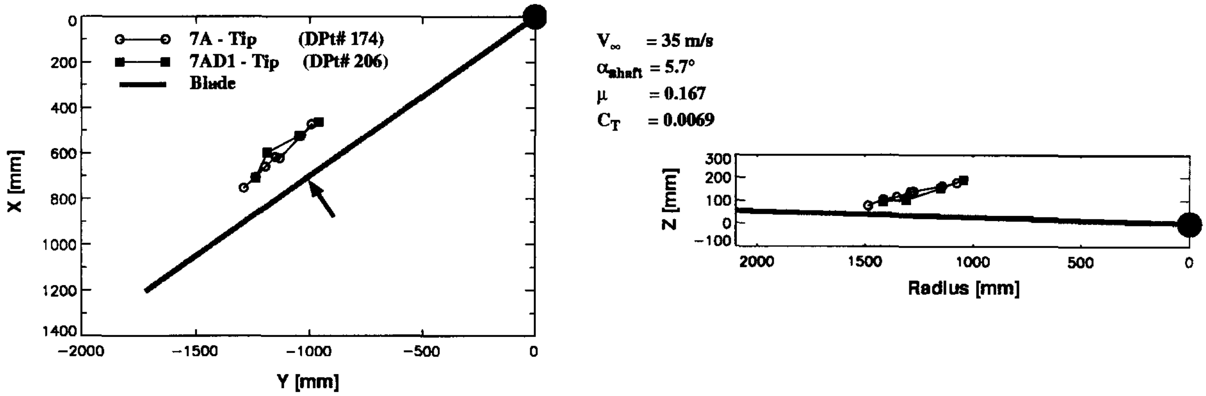


Fig. 3.15 Vortex trajectories determined by LLS technique at a blade position of 55 ° azimuth for a moderate speed descent condition

various radial stations of the 7AD1 rotor blade was determined by means of DLR and ONERA Euler/Navier-Stokes-methods. As shown in Fig. 3.16 both the ONERA and the DLR predictions[35] compare well with the experimental results for the considered lifting hover case with realistic tip speeds, although it was found that the accuracy of the results strongly depend on correctly modelling the wake.

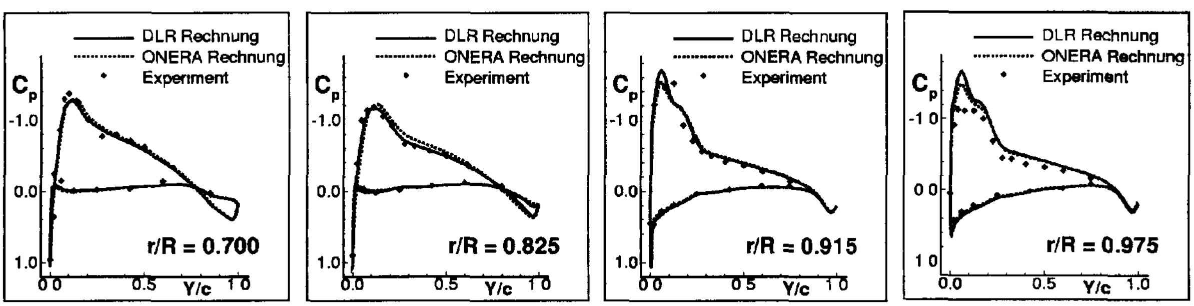


Fig. 3.16 Comparison of predicted and measured surface pressure coefficients

For conditions of fast forward level flight (with lift) the measured and predicted C_p-distribution for the 7AD1 model rotor appears in Fig. 3.17. The predictions are based on a full potential CFD-method jointly developed by European HELISHAPE-partners[36]. The code accounts for blade dynamics (as computed with the Eurocopter France R85/METAR-code) and utilizes a suitably selected inflow model. In the figure, the C_p-distribution is shown for one radial blade position near the tip and at various azimuthal positions; operational conditions are $M_h = 0.616$ and $\mu = 0.355$, constituting a transonic high tip speed condition. The appearance and disappearance of the shock development on the upper blade surface over a rotation range of $60° < \psi < 150°$ are clearly visible. Best agreement is seen where the flow is subsonic ($120° < \psi < 180°$), while data agreement is adversely affected by deviations in the predicted and measured shock positions, probably a result of the actual torsional characteristics of the experimental blade, not fully accounted for.

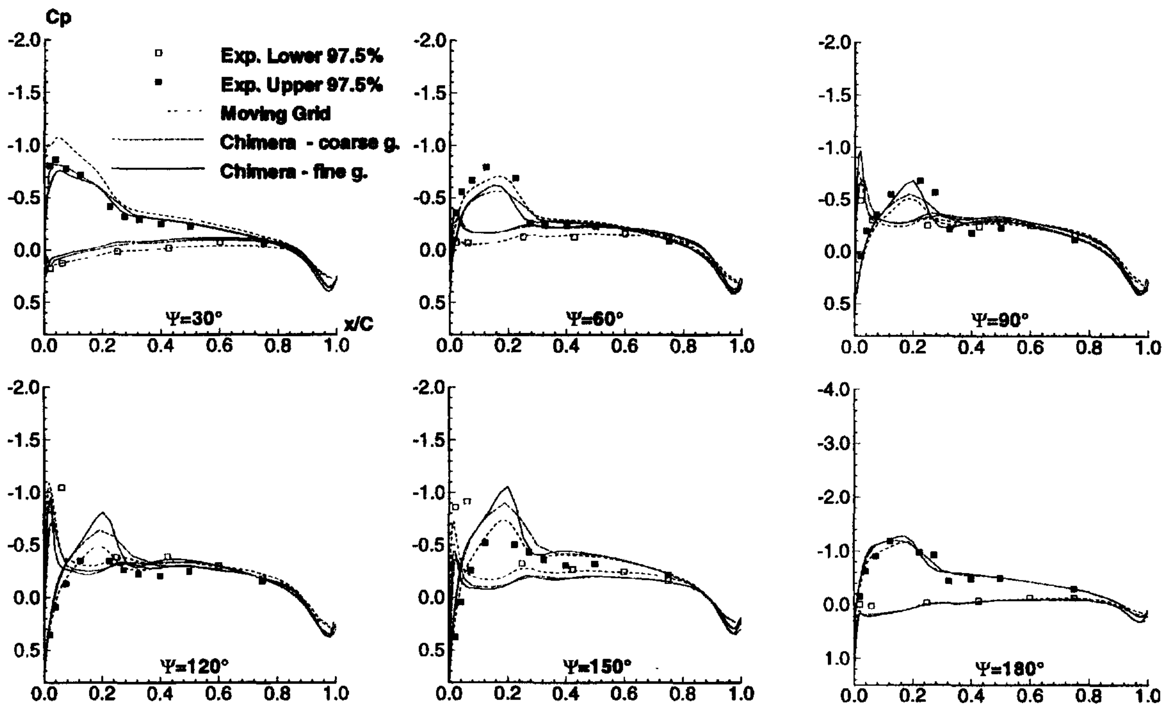
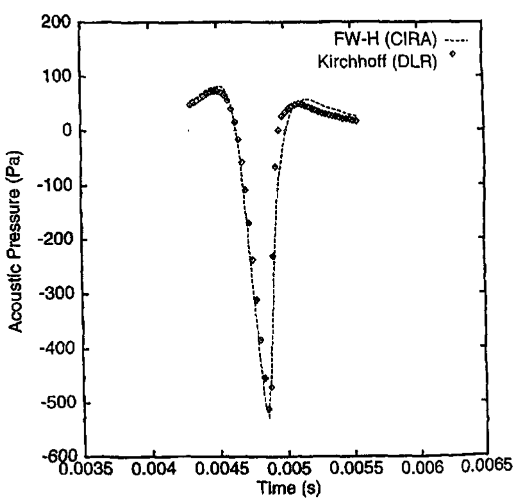


Fig. 3.17 C_p **distribution of the 7AD1 model rotor in high speed level flight at r/R = 0.975 for different azimuth positions**



Regarding rotor acoustic radiation for a high speed rotor situation (without shock delocalisation), a typical result of the theoretical HELISHAPE effort appears in Fig. 3.18. Here results derived from (a) the acoustic analogy approach and (b) a Kirchhoff integral formulation with a CFD derived near-field close to the rotor indicate good agreement of both approaches.

Fig. 3.18 Comparison between FWH and Kirchhoff results for a high speed impulsive noise pressure time history

3.3 The Joint European/US-Project HART

A joint European/US research programme was to investigate the potential of higher harmonic blade control on reducing BVI noise and to identify the key parameters for the reduction of noise and vibrations. The project utilised the HELINOISE absolute pressure sensor equipped BO 105 40% model rotor in the DNW but with a blade control mechanism that allowed to superimpose harmonic (sinusoidal) motions to the cyclic pitch variation of the rotor by means of non-rotating actuators acting on the swash plate. The objectives, namely the clarification of the aeroacoustics mechanisms affecting the phenomenon of BVI were to be achieved by simultaneously measuring the aerodynamic pressures on the blade and the acoustic radiation. Moreover several non-intrusive flow visualisations and flow field measurements as well as an interferometric method were to be employed to determine the blade deformation without and with the application of HHC.

Descriptions of the HART-effort appear in [37, 38] with key results being detailed in [39].

The principle of HHC is shown in Fig. 3.19. In case of a 4-blade rotor, swash-plate affixed actuators allow the generation of a 3-, 4-, or 5- per revolution pitch angle variation with an arbitrary phase shift ϕ_c relative to the rotor azimuth ψ. By varying this phase and the HHC-amplitude, the (1) vortex circulation (vortex strength at the instant of generation), the (2) blade vortex separation distance and the (3) bound circulation at the instant of blade vortex interaction are affected. Fig. 3.20 illustrates how these 3 parameters ultimately influence the intensity of the BVI event. It was one of the major objectives of the HART study, to rate and rank the importance of these parameters.

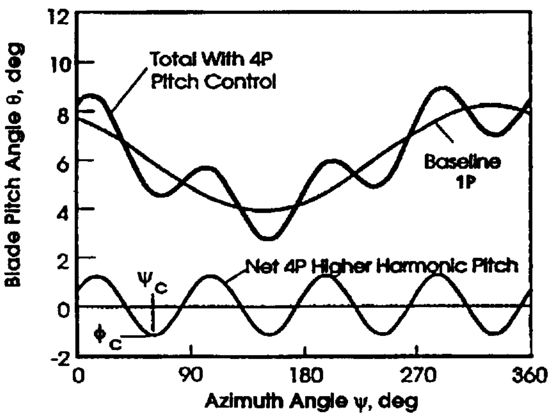


Fig. 3.19 Higher Harmonic blade pitch angle variation

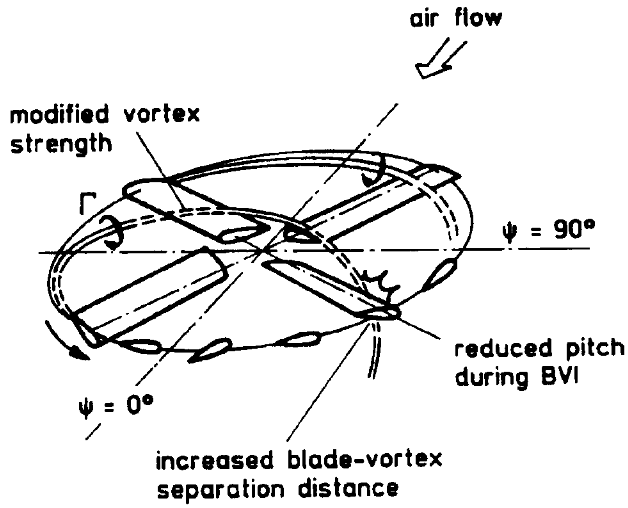


Fig. 3.20 Noise reduction mechanism by Higher Harmonic rotor Control

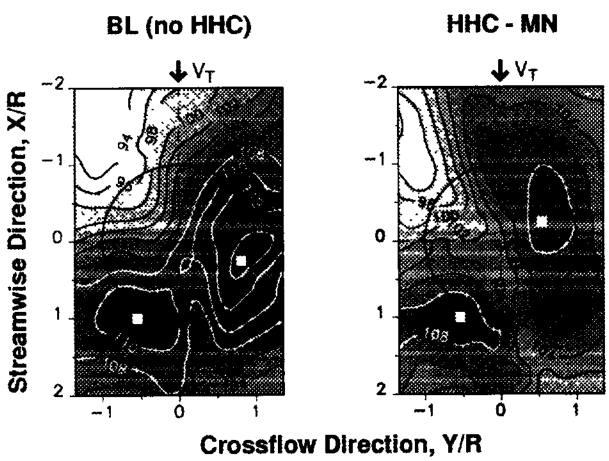
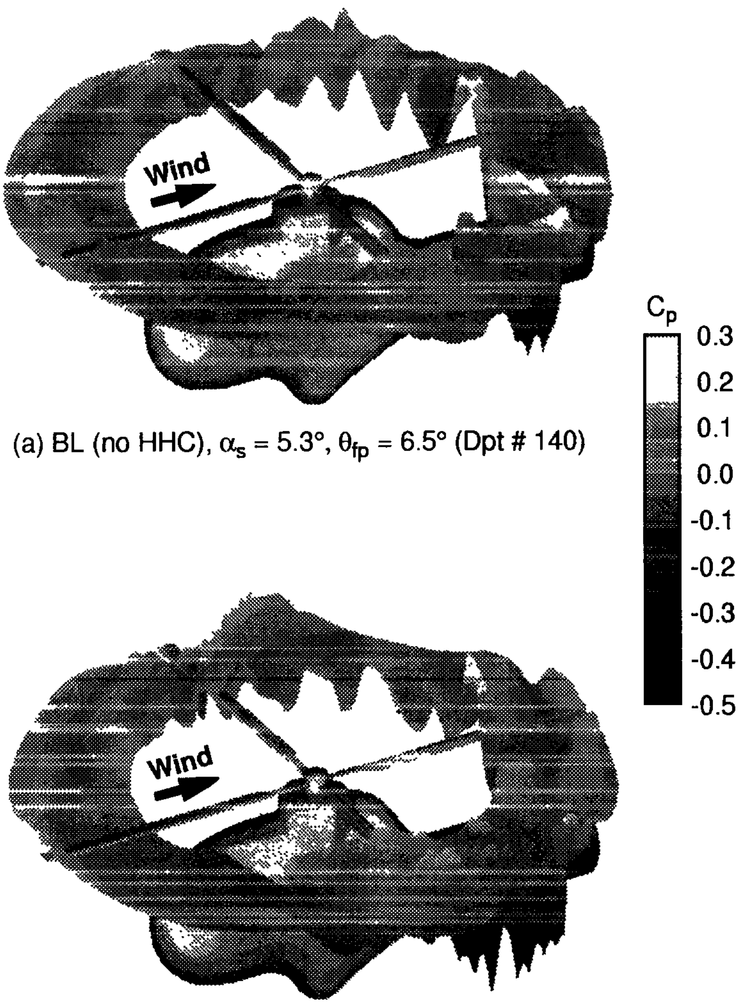


Fig. 3.21 shows the radiated acoustic field under the rotor for a simulated moderate speed (33 m/s) 6°-desent flight without (left) and with (right) the application of a 3-per-rev HHC with an optimum phase and amplitude input. Obviously, the BVI impulsive noise maximum under the advancing side is drastically reduced (by about 6 dB).

Fig. 3.21 BVI noise pattern below the rotor without and with HHC application

The leading edge pressure distribution over one rotor revolution - as depicted in Fig. 3.22 - reveals that HHC has caused the parallel vortex interactions in the 1st and the 4th rotor quadrant to be shifted towards the 2nd and the 3rd quadrants where the interaction is no more parallel to the blade and hence acoustically much less effective.



(a) BL (no HHC), α_s = 5.3°, θ_{fp} = 6.5° (Dpt # 140)

(b) HHC-MN, α_s = 5.3°, θ_{fp} = 6.5° (Dpt # 138)

Fig. 3.22 Upper surface leading edge blade pressure C_p distribution near the leading edge (at x/c = 0.03) for low speed descent base line cases without and with HHC for minimum noise

In-depth analyses showed that HHC has effects on the local blade lift distribution (which can be derived from the measured blade pressures) and thus consequently on the strength of the tip vortex, the vortex formation process, the local downwind geometry and hence the vortex structure as such (e.g. the appearance of a single vortex or a double vortex, the vortex core diameter and the blade-vortex distance during interaction).

Accordingly, Fig. 3.23 shows for both the baseline case without HHC (-> left) and the case with HHC (-> right) the radial/azimuthal lift distribution in the outer blade region, the blade-vortex distances for two vortices (# 5 and # 6) in the first rotor quadrant (at ψ = 35°) and the local blade deformation in the flap-direction at the location of the vortex generation in the 2nd quadrant (at ψ = 130°) as well as the actual interaction location (at ψ = 60°). Clearly, through HHC (the case shown on the right half of Fig. 3.23) there occurs a strongly increased lift in the 2nd quadrant when the vortex is generated, which causes a strong downwind field behind the rotor blade resulting in a downward convection of the downstream moving tip vortex. This additional downward movement must be considered as the prime reason for the increased blade vortex separation distance by more than one blade chord. A significant decrease in noise is the result. A slightly less pronounced contribution to that noise reduction is caused by blade deformation.

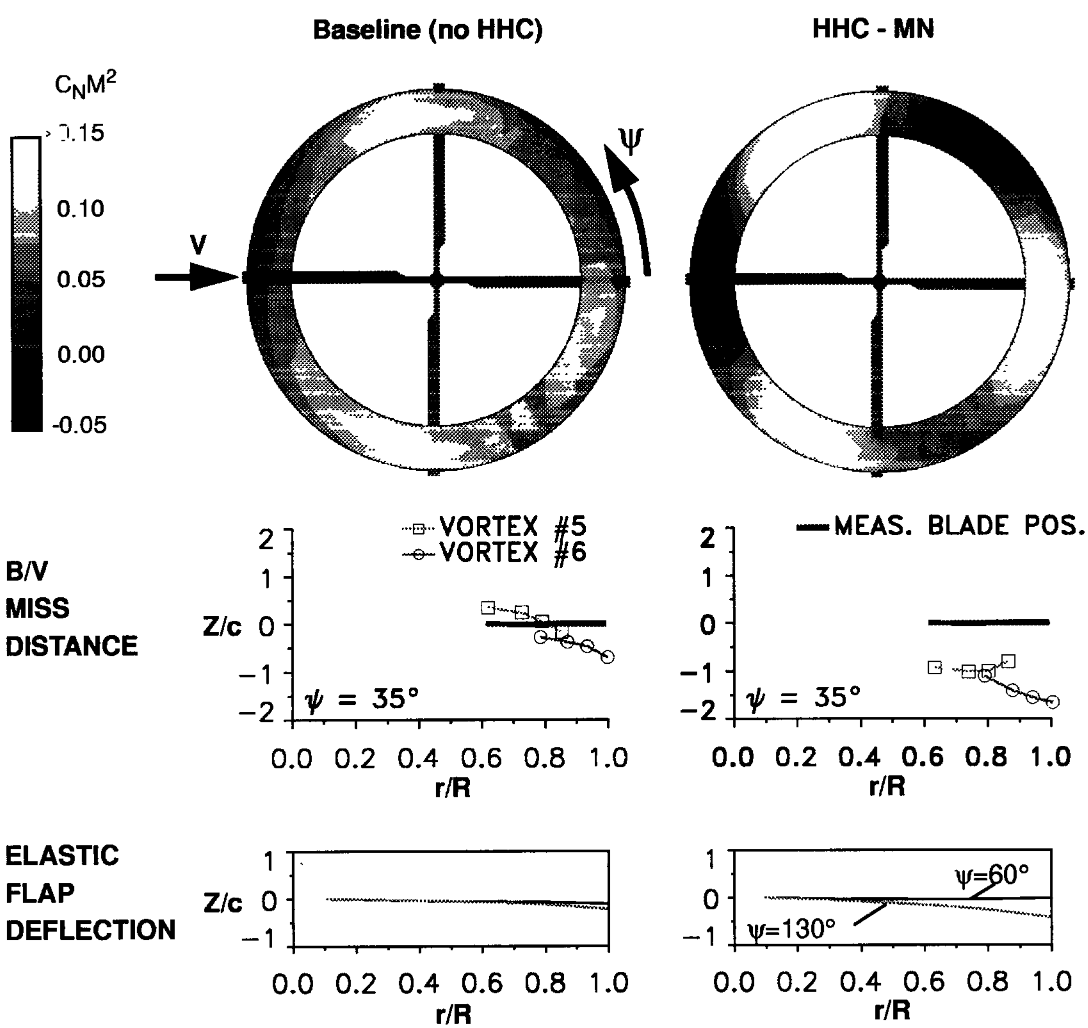


Fig. 3.23 Effect of HHC on local normal force distribution on the rotor disk, on blade vortex separation distance and on elastic blade deformation at the locations of vortex emission (ψ= 130°) and vortex interaction (ψ = 60°) for the base line case and with HHC

Hence, one of the most significant results of the HART study is the understanding of the importance of the separation distance in affecting the strength of the BVI-phenomenon whereas vortex strength might be of lesser influence.

One of the novel measurement techniques applied in the HART effort was the *Projected Grid Method (PGM)*[40] to determine blade deflections. Conventionally, blade deflections are determined by using strain gauges mounted on the blade (close to the root). From the measured blade moments one may compute the torsional, flapwise and lagwise (in-plane) deflections along the blade. The strain gauge technique provides results for all azimuth angels (e.g. time histories of the deflections).

In contrast, the PGM is an optical, non-intrusive measuring technique. The principle is based on the projection of a symmetrical bar pattern from a certain direction on top of the surface of the blade to be measured. This bar pattern is recorded by a video camera from a different direction. As the blade is deformed or displaced the bar pattern changes accordingly to show up in the image received by the camera. Fig. 3.24 shows the geometric principle of the PGM-system. A typical result - in terms of the difference in blade tip deflection of the HHC-caused minimum noise versus the baseline case (without HHC) - of a PGM- and a strain gauge-determined elastic flap deflection at blade azimuth positions of $\psi = 60°$ and 130° is shown in Fig. 3.25.

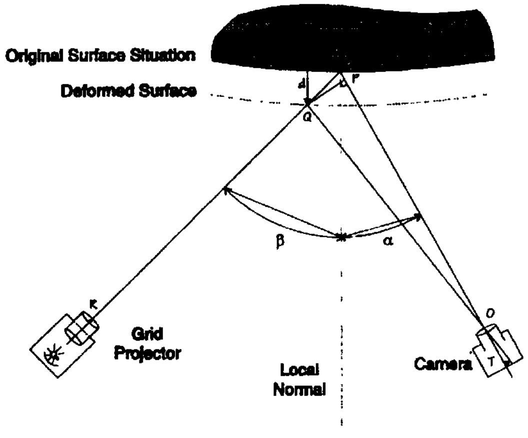


Fig. 3.24 Principle of the Projected Grid Method (PGM)

To quantitatively investigate the flow field around a rotor blade in three dimensions a highly advanced technique - again first applied on helicopter rotors in the HART experiments - is the *Laser-Doppler Velocimetry (LDV)*. Details of the procedure are reported in [41]. In the HART-project, there were in fact two such systems utilised simultaneously (by the French and the German partners, respectively), one focusing at an area on the advancing side, the other on the retreating side of the rotor. A schematic of one of the LDV-systems used with a focal length of an impressive 5 m, the distance necessary to position the equipment outside of the free-stream tunnel flow appears in Fig. 3.26. Fig. 3.27 shows a photograph of the installation of the two LDV systems in the DNW to look at the regimes of, respectively, advancing and retreating side BVI.

The LDV measurements served to acquire quantitative information on the vortex structure, the vortex strength (circulation) and the core size of those vortices interacting most intensely with the rotor blades on the advancing and on the retreating side. In addition more insight into the effects of HHC variations on these parameters was expected.

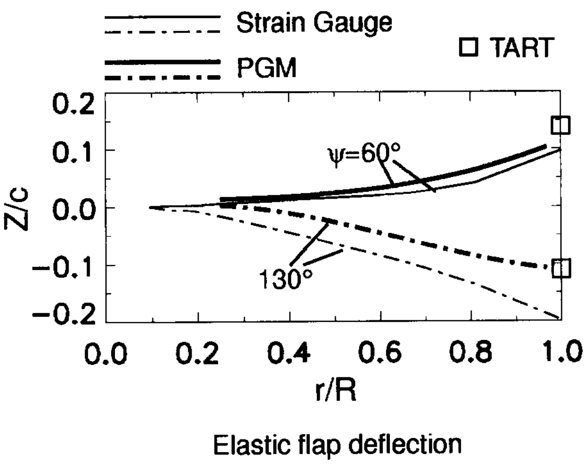


Fig. 3.25 Elastic flap deflections as determined through the projected Grid Method

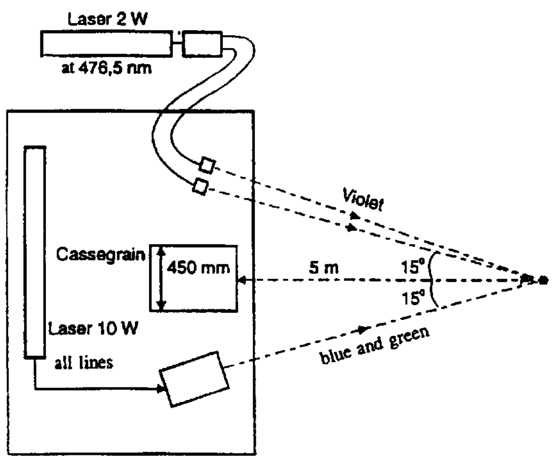


Fig. 3.26 Schematic of 3-D LDV system

LDV also needs seeding with an appropriate aerosol (incense smoke and oil aerosol, respectively). The smoke probe was installed about 50 m upstream in the settling chamber of the wind tunnel and could be remotely controlled for optimum positioning. The optical systems operated in the back scatter, off axis, mode and used the most intense laser light components at the violet, blue and green wavelengths provided by Argon lasers of 6 to 10 Watt. The dimensions of the probe volumes were very small indeed with a fraction of a mm in diameter and 1 mm length.

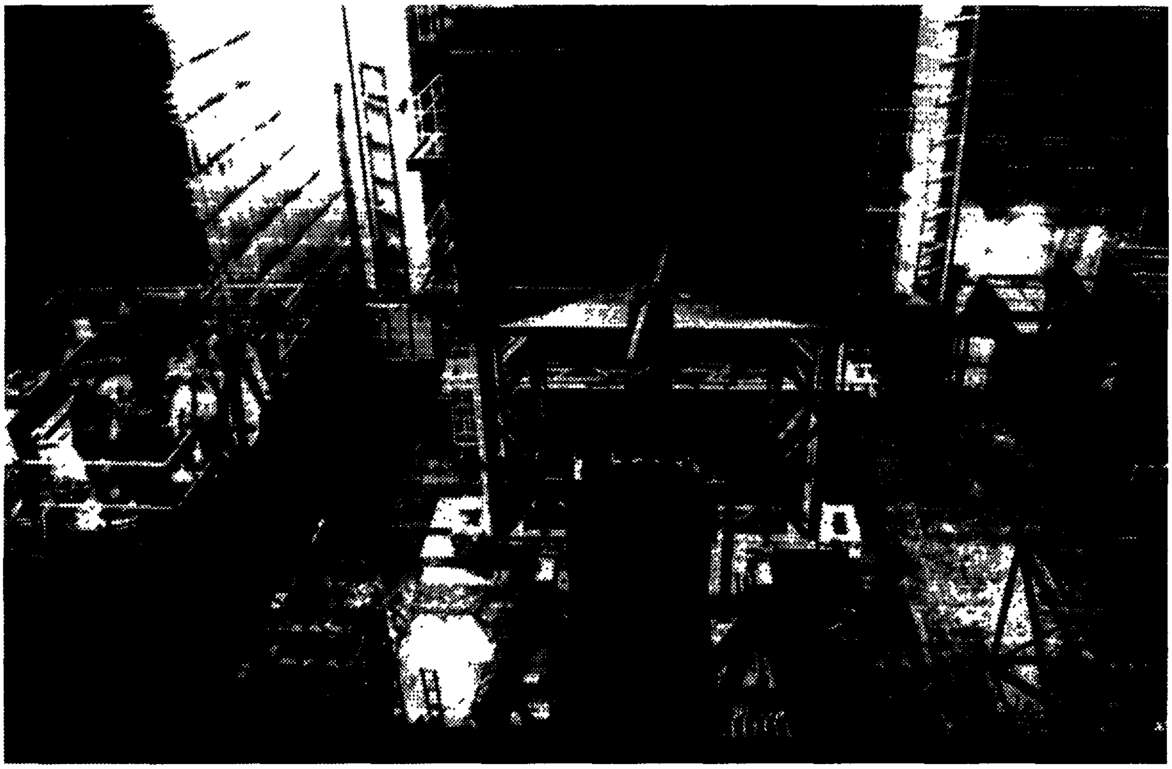


Fig. 3.27 Arrangement of the two LDV systems and the rotor rig in the DNW; view upstream towards the tunnel nozzle

In Fig. 3.28 the tip vortex velocity fields for conditions of a moderated speed descent as measured by the LDV systems are presented for locations at $\psi = 55°$ at r/R = 0.75 (advancing side -> left half of the Figure) and at $\psi = 298°$ at r/R = 0.8 (retreating side -> right half of the Figure). The vortex encountered on the advancing side had an age of approximately 460°, the one on the retreating side of 440°. For the baseline case, i.e. without HHC-application (top portion of Figure) the vortex structure on the advancing side appears rather extended, probably a result of it having already experienced several prior interactions. In contrast the vortex structure on the retreating side is well focused having evidently experienced fewer interactions. Applying HHC (lower part of the Figure) reveals almost no vortical structure under the advancing side, probably because the vortex was displaced away from the measuring volume. The retreating side vortex is well defined, though less intense.

Moreover, tip vortex core size and vortex strength can be derived from such LDV data. Fig. 3.29 illustrates how from the distance between the extrema of typical velocity curves (say in the vertical plane) the extent of the core („core-size“) may be determined. In the case shown the core size corresponds to approximately ½ of the chord.

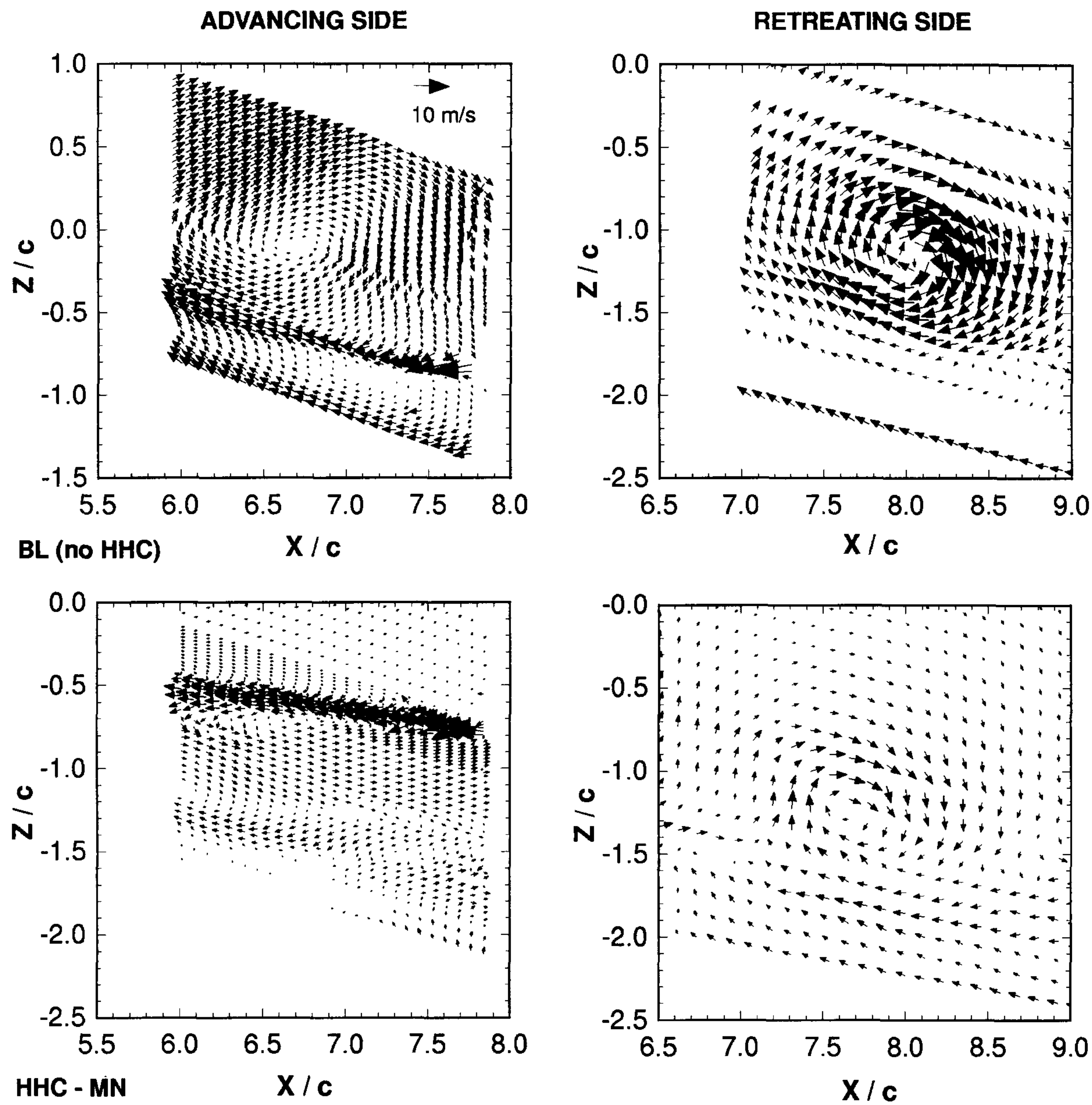


Fig. 3.28 Velocity fields in the vicinity of the blade tip for baseline case and minimum noise case for conditions of moderate speed descent on the advancing and the retreating sides

The HART programme was accompanied by post-test and pre-test aeroacoustic predictions for test cases with and without HHC. Although significant code improvements were made by all the partners, it was concluded that more precise information is needed on the rotor wakes, particularly on the development of the tip vortices (roll-up, ageing, single or double vortex formation, core size, and strength) and its geometry when convected downstream. In fact the planned RODOS-project is to provide just that information. Improvements of the free wake codes are essential for an accurate prediction of BVI geometry and thus of the unsteady airloads which are in turn required to predict the noise reduction benefit of active blade control techniques like HHC or IBC.

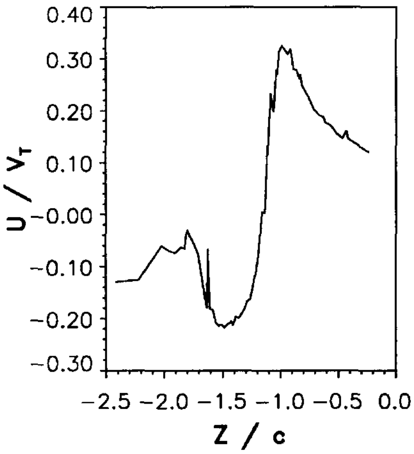


Fig. 3.29 Radial velocity profiles through the vortex core near Ψ = 300° (retreating side) and r/R = 0.8 for moderate speed descent case

3.4 The Joint European/US-Project on Individual Blade Control (IBC)

While HHC offered measures on reducing BVI-noise albeit with certain penalties by increasing rotor vibrations, individual blade control (IBC) was expected to overcome some of these difficulties. Within a joint European/US-project on individual blade control involving ECD, DLR, the German company ZF Luftfahrttechnik and scientists from the NASA Ames Research Centre, a project was initiated to evaluate the capabilities of an IBC-system to suppress BVI, while at the same time increasing rotor performance and reducing rotor oscillatory loads and rotor vibrations. The effort is described in detail in [42]. Comparisons of IBC versus HHC-capabilities are discussed in [43].

The shortcomings of the HHC in the fixed system is that the pitch angle of one blade cannot be changed without affecting the blade pitch of all the other blades. For IBC application the conventional blade pitch links are replaced by servo-hydraulic actuators. Already in 1990 appropriate flight worthy actuators had been developed by Henschel Flugzeugbau (the predecessor of ZF Luftfahrttechnik) and flight tested[44]. Some initial flyover noise measurements indicated a noise reduction potential of IBC but at that time the control authority of the IBC was rather limited and no detailed parametric variations were possible. A new IBC-system with improved control authority was developed and installed on a full scale 4-blade BO 105 rotor assembly on the NASA/US-Army Rotor Test Apparatus [45] to be tested in the 40 by 80 ft Wind Tunnel of the NASA Ames Research Centre.

Fig. 3.30 shows the set-up in the Ames wind tunnel. Acoustic data could be obtained by means of two movable (8.7 m upstream and 2.5 m downstream re rotor axis) microphones under the advancing side and one fixed microphone under the retreating side.

The IBC-actuators apply high frequency control inputs at the blade root in the rotating frame. Due to structural limitations only 2nd through 6th harmonic inputs were possible. Similar to the HHC procedure, IBC uses single frequency sine wave inputs where however the function is shifted by 90° for each blade in the same way over the rotor azimuth.

To affect the noise radiation it is necessary to again identify (1) the azimuthal rotor position where the vortex (to later interact with the blade) is generated and (2) the actual location of blade vortex interaction. For the typical maximum BVI case of the BO 105 rotor, BVI occurs in the 1st quadrant near an azimuthal position of around $\psi = 60°$ while the interacting vortex had been generated at around $\psi = 120°$. If the blade tip motion is manipulated for either or both of these azimuthal positions then effects on noise radiation could be expected.

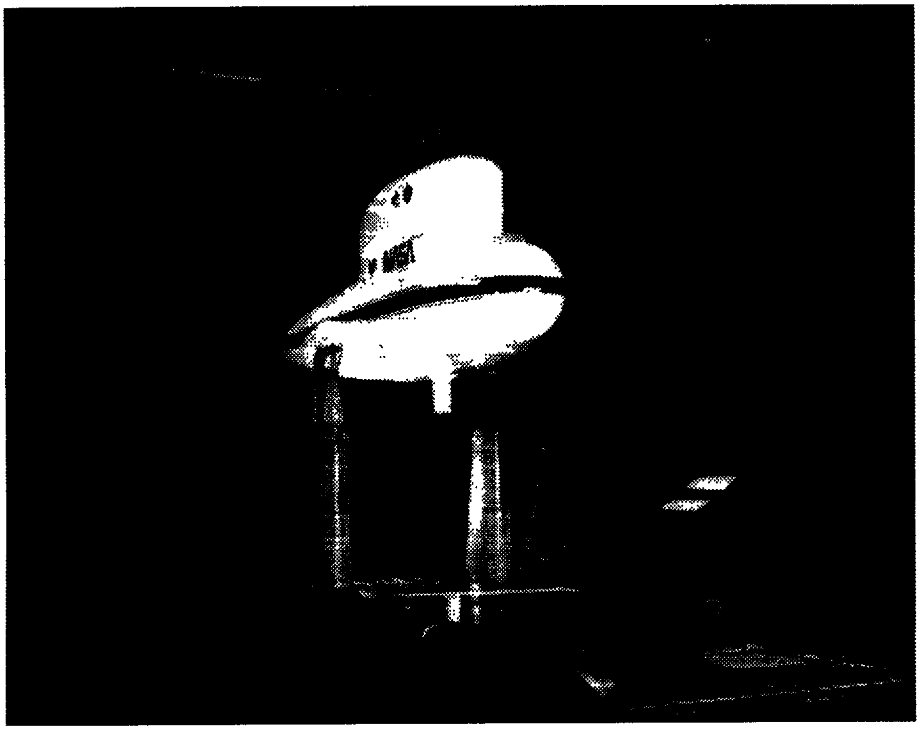


Fig. 3.30 Installation of BO 105 full scale rotor in the Ames 40 x 80 ft wind tunnel for IBC studies

For the 2/rev and the 3/rev harmonics, the largest reduction in the baseline noise were observed when the position of the first negative wave in the rotor control input was positioned around these azimuthal regions. If the negative wave was outside of these regimes, noise in fact increased. This is illustrated in Fig. 3.31 where the dependence of the observed acoustic signal strength on the azimuthal location of the first negative wave is shown for the case of a 2/rev input.

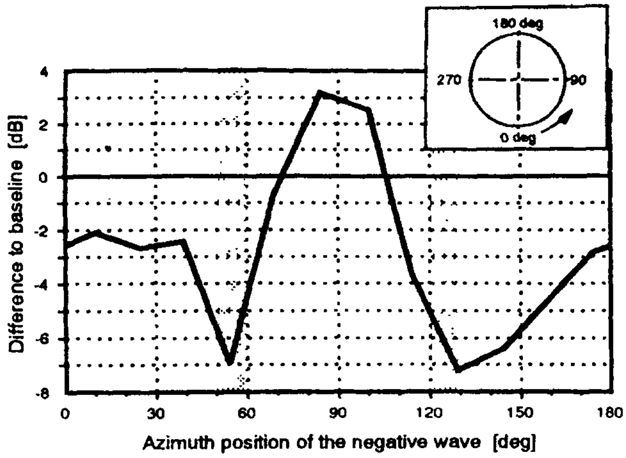


Fig. 3.31 Variation of SPL for 2-per-rev IBC input function vs. the position of the maximum negative amplitude on the advancing side ($0° < \Psi < 180°$)

In addition to being a function of the IBC phase BVI noise is also affected by the input amplitude. An amplitude sweep from 0.4° to 1.2° was conducted for the 2/rev. harmonic input to reveal that already for 0.4° a substantial reduction is achieved, while higher amplitudes provide only marginally better noise reduction. This finding is quite important since even under a 2/rev condition no large inputs are required to reduce noise.

On the retreating side, best results were observed when the IBC inputs occur at a 220° azimuth, the region where the vortex, causing retreating side BVI, had been generated. Interestingly, no benefits were observed when IBC-inputs were applied at the azimuth location of the very BVI.

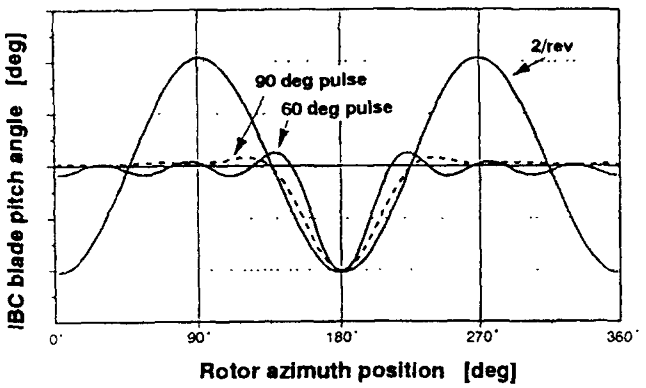


Fig. 3.32 Definition of multi-harmonic input functions (pulse at blade root or wavelet at blade tip) compared to a 2-per-rev single frequency input function

A major convenience of the IBC system lies in its ability to introduce combinations of harmonics starting at the 2/rev input mode. Special blade pitch functions can be formed by Fourier synthesis. The advantage being that dedicated negative pulses without overshoots into the positive regime (as unavoidable for a strictly harmonic input) of desired (azimuthal) width and amplitude could be generated, as illustrated in Fig. 3.32. For example, only one negative input wave of, say, 90° „width" and 0.4° „depth" per one revolution could be superimposed onto the one/rev cyclic pitch whereas the remaining 270° azimuth were totally unaffected. The question remains, where to best put this negative „dip". Corresponding optimisation tests revealed that the dip need not necessarily be positioned at either of the two important azimuth positions, namely the location of vortex generation or of BVI. Rather was a location of this dip somewhere near ψ = 350° most effective in reducing the noise. This clearly indicates that the resulting blade tip motion, following a certain input wave (rather wavelet), is highly dependent on the dynamic and elastic behaviour of the blade. To cause a desired tip motion the root input function looks rather different from the desired tip output function as the wavelet is not transmitted to the tip unaltered. Still, although the negative peak may be at the desired position there could be high overshoots at other ones, a consequence of the complexity of the blade torsional behaviour.

The flight tests [44] in 1990 which preceded the Ames wind tunnel tests had demonstrated a noise reduction potential of some 4 dB in flyover tests when the negative wave from an appropriate IBC input was applied at a particular rotor azimuth position for a moderate speed descent flight with maximum BVI impulsive noise. The tests however emphasised the need for a fast closed loop control system in order to control the phase with respect to reducing BVI noise generation. Accordingly, a control concept at least for the advancing side BVI noise reduction must be based on the accurate identification of the azimuth region on the rotor disk where BVI occurs. Such could be done by relying on appropriately filtered blade surface pressure sensor signals. Flight tests (to be discussed later in this paper) with a BO 105 helicopter one of whose blades had been equipped with absolute pressure sensors, indicate the feasibility of such an approach to utilise IBC for rotor noise reduction purposes.

3.5 The French-German ERATO Project

The objective of the aeroacoustics rotor optimisation programme ERATO, a joint effort between the French and German Research Establishments ONERA and DLR, was to design, build and test an aerodynamically and acoustically optimised rotor substantially less noisy under conditions of moderate speed descent (where maximum BVI was to be expected) compared to a reference rotor for a helicopter in the 4 to 6 t class. Acoustic benefits were also to be achieved for low speed and high speed level flight without penalties in vibration and performance. Although the study was considered a pure research establishment effort, Eurocopter as an industrial partner provided consultation to establish the link to helicopter operational realism and technical feasibility of the end product.

The project is to culminate in aeroacoustic proof-of-concept tests for high speed conditions in the French Modane S1 wind tunnel, and for conditions of low and moderate speed in the DNW, utilising the well established measurement techniques of blade mounted surface pressure sensors (for source studies) and the movable microphone array to measure radiated acoustics as in the HELINOISE, HELISHAPE and HART experiments.

The effort was divided into several phases: an exploratory phase where essentially aerodynamic and acoustic codes of the French (ONERA) and German (DLR) partners were to be improved and validated on the basis of previous wind tunnel results (including HELINOISE) pertaining to rectangular and rigid blades. Within the subsequent main phase several acoustically optimised rotor geometries with non-rectangular and elastic blades were defined accounting however for technical and flight operational constraints (performance, vibration, weight and operational flight envelope). The final phase comprised the structural design and manufacture of the blades and a study of possible additional acoustic benefits by application of HHC, as well as the validation wind tunnel tests.

In the course of the parametric optimisation studies within the ERATO-effort, DLR, to predict BVI impulsive noise for different blade designs by means of its acoustic code, determined the necessary rotor trim and performance as well as wake aerodynamics inputs through a rotor simulation code which is based on unsteady non-linear lifting line theory; a prescribed wake (Beddoes) with options for rigid or elastic blades was used to yield high resolution blade *loadings* as input into the linear dipole term of the FWH-equation. In a different approach, the quasi-steady formulations of DLR's „lifting body surface panel method“ were used, employing a free wake model and also accounting for the blades' aeroelasticity to yield high resolution unsteady blade *pressures* as inputs into the FWH-equation.

For the same purpose ONERA had developed a very successful aerodynamic/acoustic BVI prediction chain which accounts for the all-important vortex roll-up process. The trim characteristics of the rotor are determined by the „R85/METAR-code“ to yield both the rigid and elastic blade motions. The (free) wake geometry is predicted by the „MESIR-code“ to yield vortex sheet location and intensity. Subsequently the „MENTHE-code“ provides the rolled-up vortices locations and intensity, whereupon the blade unsteady pressure distribution is determined by the „ARHIS code“ as input into the FWH equation.

For high speed noise assessment in the ERATO studies, DLR employed an Euler-code while ONERA used a full potential 3D-code. However in view of the parametric blade developmental approaches taken, no extensive computational exercises were conducted in the ERATO-effort concerning the non-linear quadrupole source; linear methods were considered sufficiently accurate to predict the noise even at the moderately high speed forward flight conditions where however the blade tip speeds as such would never enter regimes with shock delocalisations.

The variable parameters considered in the ERATO exploratory phase - initially for a rectangular tip shape blade - pertained to hover tip Mach number, number of blades and chord length. From the more than 20 parameter combinations very few optimum configurations were established which (in theory) were to provide substantial noise reduction vs. the reference rotor at reduced power consumption. While tip speed reduction was - expectedly - a major parameter in reducing the noise, the industrial partners set a sensible lower limit that would still allow safe and economic operation of the rotor.

Within the ERATO main phase pertaining to more advanced rotor blade and tip shape configurations, additional geometric parameters were included in the optimisation process, such as blade profile, profile distribution along the chord, twist distribution, chord length distribution and blade sweep. Now accurate free wake computations became necessary and the vortex roll-up processes had to be accounted for.

In the end a sophisticated blade geometry was developed which - from the computations - showed significant promise in being both a technically and operationally feasible blade configuration. The blade should generate significantly less noise at BVI and still show acoustic improvements under conditions of high speed flight, while providing a performance at least as good as the reference rotor. The aeroacoustic wind tunnel experiments, now planned in 1997/1998, will show whether the expectations are fulfilled.

3.6 Wind Tunnel/Flight Test Validation Project (FLYVAL)

As had been well established in the previous research projects HELINOISE, HELISHAPE and HART, understanding rotor noise hinges to a large extent on understanding the unsteady aerodynamics on and near a rotor blade. Here unsteady blade surface pressures in their dependence on rotor geometry, rotor elasticity and rotor operational conditions, were found to constitute a key source of information.

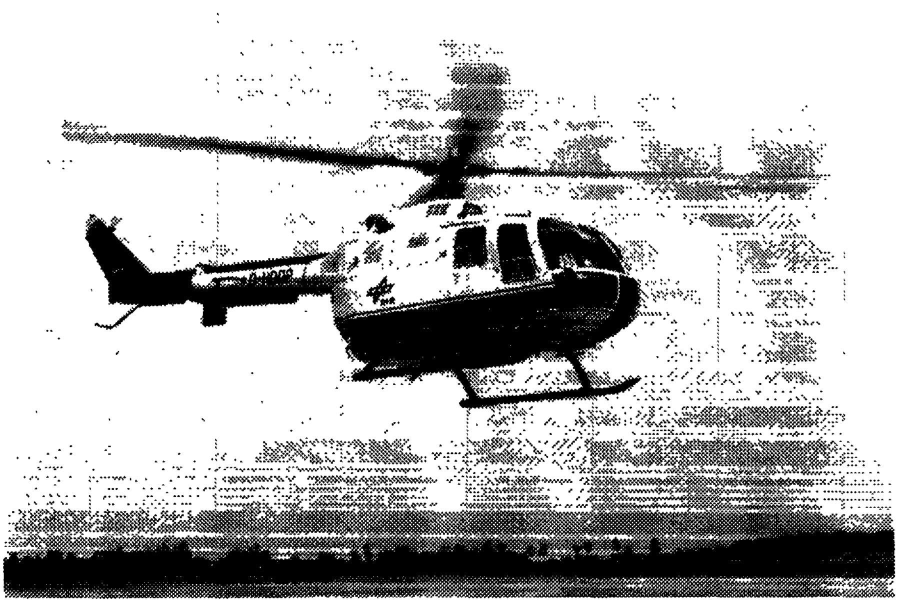


Fig. 3.33 DLR flight test helicopter BO 105 for inflight blade surface pressure measurements

Although the scaling factor in the experiments where the BO 105 main rotor model was employed (such as in HELINOISE and HART) was quite large (namely 0.4), thus implying good scalability towards full-scale, proof of the validity of the data and their transfer to a realistic flight vehicle situation was still lacking. No comparable aeroacoustics information employing the „full-scale counter-part" of the model rotor was available. A first dedicated experiment[46] to measure blade pressures on the DLR BO-105 helicopter (Fig. 3.33) was initiated (under the acronym FLYVAL), to clarify whether operational parameters of wind tunnel and flight tests can be duplicated and how well blade pressure data obtained in wind tunnel model and in flight tests would agree.

There were only 20 sensors on the (full-scale) BO 105 rotor blade (compared to the 124 on the model blade), albeit at strategic locations. On the flight test helicopter blade, one chord section (r/R = 0.87) was „heavily" instrumented on the upper and lower surface with 13 sensors, additional sensors were positioned near the leading edge at radial stations 0.60, 0.80 and 0.97. The exemplatory data presented in the following pertain to a moderate speed descent case with strong BVI. It was observed though that - in the flight speed range around 30 to 35 m/s - there seemed to be a constant bias between the actual (for the flight tests) and the simulated (for the wind tunnel tests) flight path angles of approximately 2° to 3° for best agreement of the respective blade pressure data. This is illustrated in Fig. 3.34 where pressure time histories

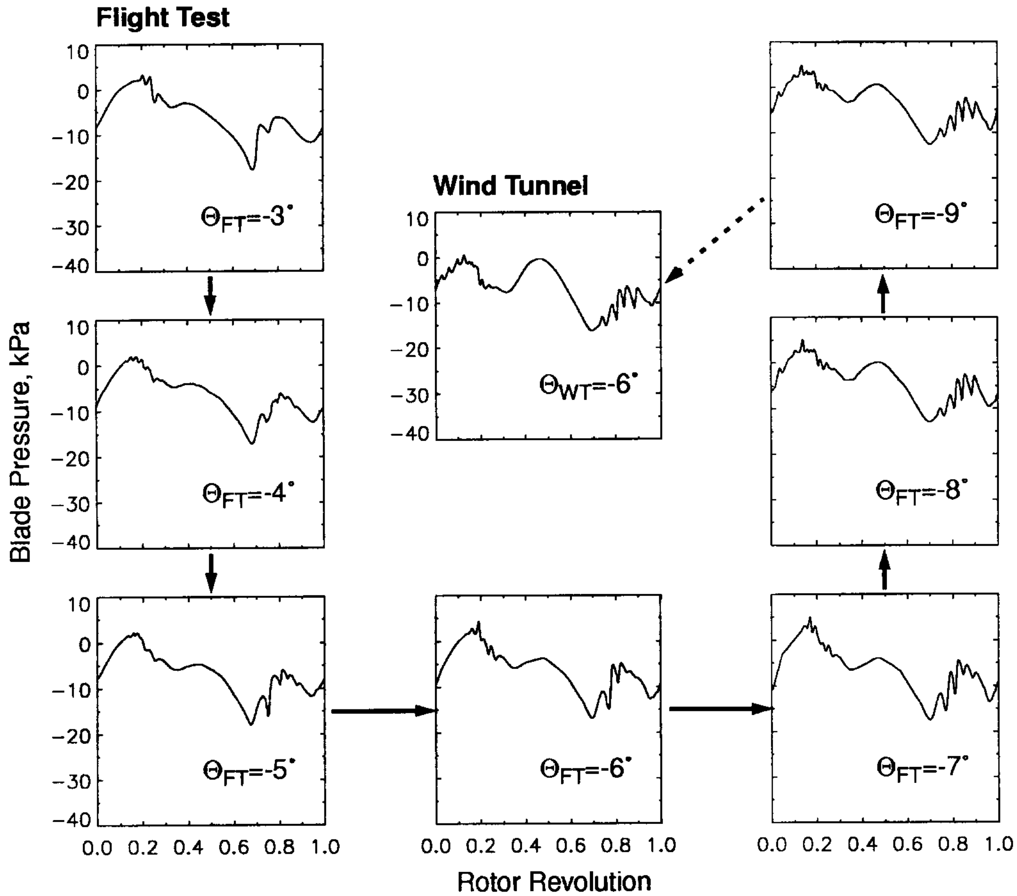


Fig. 3. 34 Comparison of blade pressure time histories for flight path angles ranging from -3° to -9° with one obtained in the wind tunnel at -6° for conditions of moderate speed descent with strong BVI

(PTHs) for a nominal flight speed of 32 m/s and descent angles varying from 3° to 9° in one-degree steps obtained from one upper surface sensor at r/R = 87% and at a 3% chord location are shown. Comparing these seven PTHs from the flight tests with the model scale 6°-descent case indicates best agreement for the full-scale 9°-descent case. Disregarding this angle-deviation, agreement of flight and wind tunnel data is excellent. For example, each individual spike - both in time and amplitude - of a sequence of blade vortex interactions is well duplicated. Comparing the upper surface blade pressure contour plots (in terms of the nondimensional pressure coefficient C_p) over one revolution, (Fig. 3.35) again for the case of a moderate speed (32 m/s) nominal 6°-descent, clearly reveals the traces of blade vortex inter-

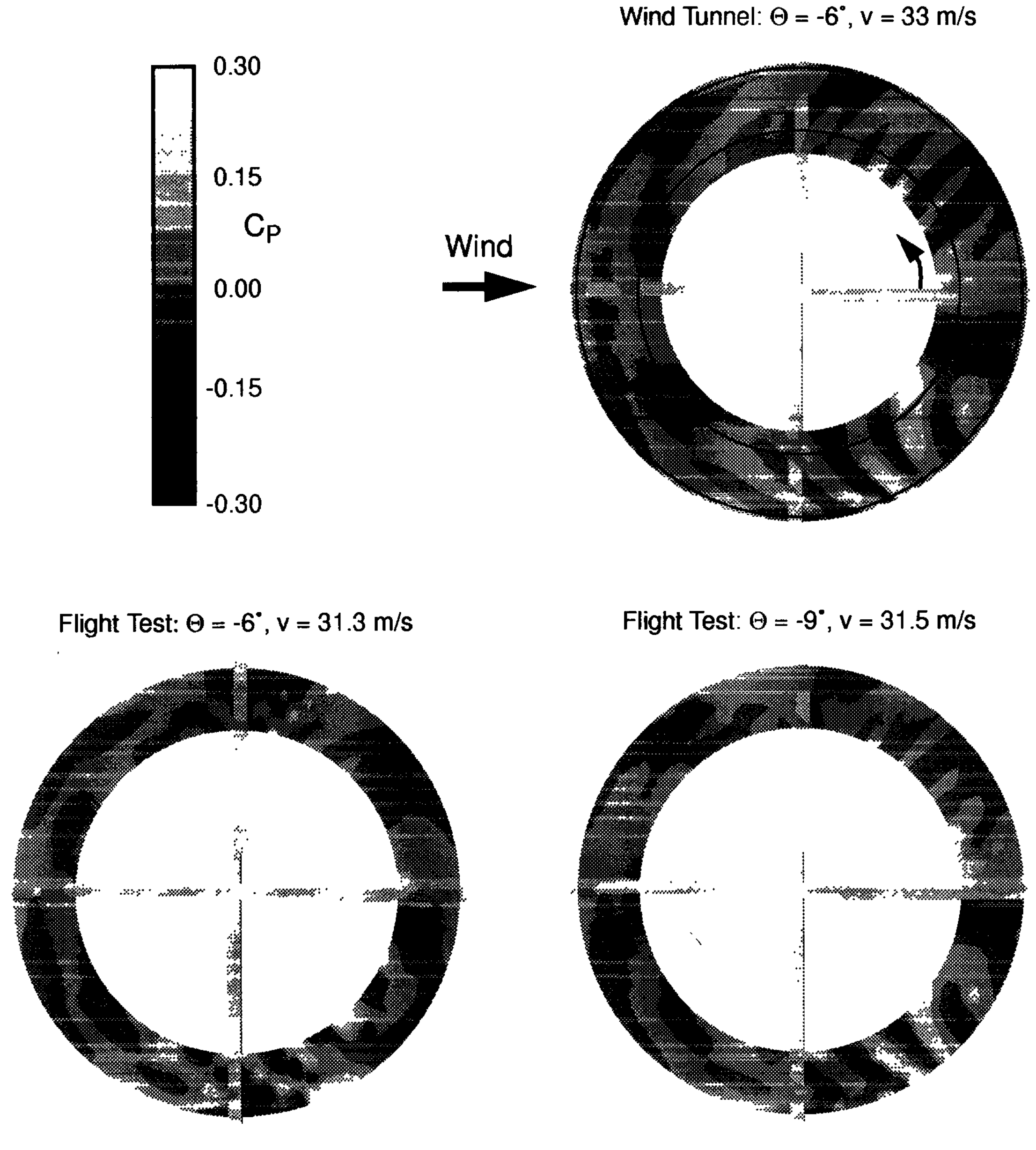


Fig. 3.35 Blade pressure contour plots generated from upper surface leading edge sensor data for a moderate speed descent condition with strong BVI

actions in the first (advancing side) and fourth (retreating side) rotor quadrant. In the Figure, the top circular plot relates to the 6°-descent model case, the lower two plots to the flight test situation. Here, the left one pertains to a nominal 6°-descent case, whereas the right one to a nominal 9°-descent case, this one indicating an excellent agreement with the 6°-descent case of the wind tunnel model test.

A number of reasons for this „bias“ could be advanced. For one, in establishing a wind tunnel test condition, the important parameters advance ratio, tip path plane angle and thrust coefficient are precalculated to match a desired full-scale flight condition by using a force balance equivalency and a wind tunnel correction. Hence, to make wind tunnel and flight results to agree, the ratio of lift and propulsive force should be identical. However, the drag component - to be overcome by the propulsive force - can only be estimated for the real helicopter. On the other hand it is quite difficult in flight tests to exactly maintain the preselected conditions - forward speed, climb or descent rate, thrust coefficient etc., never mind to accurately measure these. Moreover, atmospheric conditions - wind gusts, air density, air temperature etc. - are usually also different from those under controlled wind tunnel conditions. Also in the wind tunnel tests the rotor was operated with zero flapping which is not necessarily the case in flight, such that the effective shaft angles in the two cases might differ. Finally, any difference in the aeroelastic properties of the model and the full-scale rotor blades could result in a different rotor dynamic behaviour causing ever so small, yet influential variations in the respective blade tip motions.

Still, the excellent agreement of blade pressure waveforms indicates that a match of flight and wind tunnel operational parameters should be possible; this statement is not contradicted by the - presently still not fully explained - observed bias of 2 to 3 degrees in the effective tip path planes for the tunnel and the flight tests at moderate flight speeds; better agreement seems to exist at higher flight speeds.

In all, the tests served to significantly further the understanding of realistic rotor aeroacoustic phenomena and of the reliability of model-scale tests versus the full-scale flight situation. This flight test programme was a start in the attempt to validate results of the numerous previous experimental rotor aeroacoustics programmes in the DNW conducted so far and will help in the execution and interpretation of future similar tests presently being in the planning stage.

4. The Quiet Helicopter - An Outlook

The ultimate objective must be to make helicopters acoustically non-intrusive. That is to say that (1) they must be quiet to begin with, i.e. generate as little noise as possible at any given operational condition and that (2) they are consciously flown in the quietest possible manner. European research reported in this paper has shown some ways of how to achieve that.

The question remains: how quiet can or rather should a helicopter be? This question has to be answered in the context of existing and future noise criteria. The International Civil Aviation Organisation, ICAO, and its Committee on Aviation Environmental Protection, CAEP, respectively, have established noise limits for helicopters, specified for three test procedures: a take off, a level overflight, and a landing approach. Unfortunately, the typical helicopter does not always fly at exactly these specified conditions. In fact, it hardly ever does so, and any manufacturer who would design solely for the purpose of meeting or even „beating“ these noise limits would jeopardize his chances to sell on the market. Land use considerations, and the growing tendency of airports, heliports in the subject case, to set their own noise limits and in cases even financially penalise excessive noise producers by adjusted landing fees, determine whether a helicopter is considered quiet or not, almost independent of it meeting the ICAO noise limits. In other words, a helicopter must be quiet at all operational conditions, rather than only at those very limited ones specified in noise certification.

Discussing ways to reduce noise „at the source", can be broken down into the following subjects: tip speed reduction, reduction of blade thickness, modification of the blade planform and reducing interaction noise.

Tip speed reduction is certainly the most effective way to reduce noise at the source but there are severe limitations to this „obvious solution". Indeed there are already helicopters in service which feature automatic systems to control the RPM (down to a safe lower limit) as function of ambient air pressure or by „switch-operated" RPM-control systems. In practice, for example, full RPM is flown at, say, 1000 ft above ground whereas below that altitude, i.e. close to the ground, RPM is reduced for lesser noise. That works fine at sea level. At higher geographical locations (say in countries like Switzerland) that may be difficult to implement, since density altitude is lower and full RPM is needed even at flight heights close to the ground. Moreover, there are operational risk concerning flight safety; if RPM was reduced on a twin engine helicopter flying close to the ground, an engine failure would cause RPM to suddenly go down even further and it would be difficult to get RPM up quickly enough to avoid an emergency situation.

Among other things, RPM cannot be reduced „ad libitum", because vibration damping systems are usually „tuned" to a particular RPM or a very narrow RPM-range. Moreover, limitations in reducing tip speed is countered by the need to provide the necessary thrust margin for manoeuvring flights. A further problem pertains to rotor service life. It is not so, that a low RPM is better. On the contrary, lower RPM tends to increase rotor loads and may cause structural damage such as delamination. Also, at reduced RPM, the decreasing centrifugal forces require higher flap and lead-lag bending moments thus adversely affecting the fatigue life of components. Suppose, a rotor was designed for a 10.000 hour service life; with a lower RPM that service life could easily go down to 3000 hours. Certainly, no operator would trade service life for noise reduction. I.e. a low-tip-speed rotor may not at all be acceptable to the manufacturer or the operator.

Typical tip speeds might be on the order of 235 m/s for the heavier helicopters, 220 m/s for medium weight helicopters, and 210 for the lighter ones. At least for the civil market noise-considerations may nevertheless force the helicopter manufacturers to consider reducing RPM by another 5% in the short run and perhaps by 10% in the long run with respect to their particular datum helicopter.

To compensate for any loss in thrust at reduced tip speeds the *number of blades may be increased* to increase the effective blade area. In that case each blade will also experience a decrease in load which will effectively decrease loading noise and to some extent also thickness noise. Unfortunately, more blades will raise the blade passage fundamental frequency (and its overtones) such that the A-weighted or the Perceived Noise Level (PNL) will increase, merely for that reason. More blades may however also increase the broadband noise radiation. Still, there should be some acceptable trade off between lowering tip speed and increasing blade number while minimising performance penalties on a case by case basis. Of course, the loss of thrust with decreased tip speed may also be compensated by lift augmentation, e.g. by additional wings or even by means of ducted fans. Such approaches - which would however not offer benefits under hover conditions - would in any case require major design changes.

Reducing blade thickness will inherently reduce thickness noise which is a particular problem in high speed forward flight. For structural reasons it suffices to reduce blade thickness at the outer blade regions since it is there where high speed compressibility effects take place. Still, strength and dynamic response problems may arise with thin blades.

Modifications of the blade geometry in terms of its planform offers probably the most cost-effective and least detrimental manner of reducing source noise. For example, non-rectangular swept-back tip shapes (as investigated in the HELISHAPE study) have shown to significantly reduce high speed impulsive noise. Rather than only modifying the very tip shape, a backward - or even a forward - leading edge sweep of the outer 30% of the blade will affect blade vortex interaction intensity; conceptually noise-critical parallel interactions of vortices with the blade's leading edge contour would be avoided that way, although a blade contour optimised for advancing side BVI may not be optimal for retreating side BVI.

Active control methods to reduce BVI have been investigated at great length, such as in the HART research effort. Here it was shown that higher harmonic control of the rotor blade can reduce advancing side BVI by up to 6 dB, although at the cost of perhaps increasing vibrations. Nevertheless, any HHC system could be sensibly employed only during critical BVI conditions in a moderate speed landing approach and be switched off during regular cruise. Alternatively, HHC inputs could be modified for conditions of high altitude cruise (or even high speed cruise) to reduce vibrations without regard of increased noise. It was determined, though, that certain combinations of inputs, say combining 3 + 4 per rev or 3 + 5 per rev (on a 4-blade rotor) would reduce BVI without unduly increasing vibrations.

A technically more ambitious method would be the individual control of blades as investigated in the subject joint European/US IBC-research-project reported further up. Here control inputs (say wavelets rather than sinusoidal ones) could be tailored and optimised, respectively, for the operationally dependent noise reduction requirements. It was found that a closed loop control mechanism is imperative. Such a control mechanism could use inputs from blade mounted sensors, to indicate to the control system that, for example, a BVI condition exists. IBC also offers potential to positively influence performance over large portions of the flight envelope (including manoeuvring flights or high speed flights) to alleviate stall on the rotor retreating side. But this aspect, as well as the perfection of IBC for the more conventional application still needs much future efforts. For example, there would be a need to develop input algorithms to provide an optimum trade-off between noise, vibration and performance over an extended flight regime.

The future may lie in active local blade control, LBC by means of „smart structures". Here blade pitch, blade geometry (profile shape and perhaps even planforms) are controlled directly on the blade, say by some piezo-electric devices, rather than by mechanical inputs at the blade root, as necessary for the HHC and IBC which require elaborate actuator technology. The benefits might be improvements in rotor performance by delaying stall onset and stabilising lead-lag and torsional blade motions while simultaneously reducing noise and vibration.

Although not specifically treated in the bulk of the paper, a word on *anti-torque technology* is in order. The tail rotor is both an acoustic source in itself, as it is also heavily affected (both performance- and noise-wise) by rotor wake inflows, and flows shed from the main rotor hub and the fuselage. Here, much lower tip speeds, accompanied by the use of more blades (as in the Fenestron/fan-in-fin system) and even the use of uneven blade spacing offer promising noise reduction potentials at much lesser technological risk than for main rotors. While a **No Tail Rotor** (NOTAR) system would completely avoid tail rotor noise (although some additional broadband noise might be generated), as amply demonstrated in the MDD 520N or

600N production helicopters as an alternative anti-torque system, it is nevertheless restricted to low to medium weight helicopters. Detrimental inflow into the tail rotor can to some extent be averted by aerodynamically shaping the rotor hub and by optimised positioning of the tail rotor with respect to the main rotor, although a one-for-all optimum position may not be possible, as the inflow differs greatly under different flight conditions. As will be recalled, the EU-initiated HELIFLOW-project deals with main-rotor/fuselage/tail-rotor interactional phenomena as will upcoming flight tests planned at DLR; in these cases, both the main rotor and the tail rotor will carry blade mounted absolute pressure sensors and strain gauges to allow an in-depth study of source acoustics and aerodynamics, as well as of the respective blade responses.

While all these measures pertain to affecting the source noise, there are also *flight operational procedures to avert noise*, BVI-noise in particular. The research results of the HELINOISE and HELISHAPE efforts indicated the regimes where BVI noise prevails, namely moderate speed descent conditions, as typical for landing approach. By consciously avoiding these flight regimes, substantial noise reductions of up to several dBs seem possible. These findings have however to be translated into improvements in helicopter control and handling characteristics, as the pilot needs a clear indication when he flies at such a noise-critical regime, and, more importantly, what flight-operational measures he would have to take to evade that regime. Information obtained from blade mounted sensors together with other flight operational parameters might offer a promising way to develop a flight-worthy „noise warning-system“. To effectively fly such noise abating procedures appropriate airborne control systems and ground based air traffic control techniques need to be developed.

It is to be expected that future research efforts in Europe pertaining to noise reduction at the source and by operational means will eventually lead to an industry backed full scale demonstrator. To this end, research will continue towards developing aerodynamically and acoustically optimised rotor blades, and blade geometries (tip shapes in particular), respectively. Research will further the understanding of active control systems beyond those of HHC and IBC towards LBC-systems to obtain an overall better rotor system, i.e. one that provides an optimum compromise between noise, vibration and performance.

Beyond the technical aspects, effective helicopter noise amelioration considerations need also account for the subjective human response, since noise reduction efforts as such must also be perceived (and accepted) by the public. An overall noise reduction effort will also have to include engine and gear noise, and perhaps even airframe noise. The influence of the fuselage on rotor noise, as it causes reflection and scattering of noise produced by the rotor(s) and of the rotor hub geometry must be better understood, as must be the complex interaction mechanisms of the tail rotor with the „upstream aerodynamics“. Control of tail rotor noise, a research area rather neglected in the past, will see more research efforts, and novel concepts for anti-torque generation will be investigated such as jet-based vectored thrust generators also for heavier helicopters.

All the experimental and theoretical efforts, reported in this paper are tools to achieve the ultimate goal of a helicopter, which unobtrusively blends into the acoustic background noise and is perceived as no greater disturber than other airborne or ground-based means of transportation.

5. Concluding Remarks

This paper discussed European research efforts over a time period of the past five to ten years. It was shown that substantial effort was spent - often within joint research projects sponsored by the European Union through its dedicated aeronautics initiative - to significantly improve, both through major experimental projects and theoretical advances the understanding of the aeroacoustics of rotor noise, paving the way towards dedicated source noise control. Although this paper concentrated on corresponding European efforts, many fruitful links exist with researches in other parts of the world, and indeed, many research projects of precompetitive nature are often conducted in joint projects between European and US-American research entities. Significant European research projects in the area of helicopter noise have just begun, such as the HELIFLOW-project to investigate tail rotor noise among other objectives. Others are in the final planning stage, such as the joint US/European project RODOS which - through dedicated experiments in the DNW employing the PIV-technique - should significantly improve the understanding of, and provide much needed information on, the characteristics of unsteady rotor downwash and its interaction with the elastic blades.

Theoretical efforts to predict rotor noise will concentrate on improving CFD-techniques by including free wake and blade aeroelastic models and combined CFD/Kirchhoff methods to enable the prediction of high speed forward flight under lifting conditions up to and including transonic rotor tip speeds. Within less than a decade, the complete computational description of a main-rotor/tail-rotor/fuselage system in terms of its unsteady aerodynamics and acoustics might be possible.

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