DFVLR-DYNAMIC MODEL TESTING IN WIND TUNNELS FOR ACTIVE CONTROLS RESEARCH

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Abstract

The rising demands imposed on aircraft performance and flight characteristics call for an extended use of active control systems. To investigate problems associated with the application of active control systems a technique has been developed, which allows a comprehensive treatment of flight mechanics problems including the effects of aerodynamics, aeroelastics and control systems. Since this method is a synthesis of both computer simulation and wind tunnel test, a variety of information on specific flight mechanical phenomena can be obtained. The paper deals with two experimental devices:

- the "Installation for Dynamic Simulation in Wind Tunnels" for investigation in the field of fixed-wing aircraft,
- the "Rotor Test Stand" for investigation in the field of rotary-wing aircraft.

Problems of transferability of measurement data from model to full scale are discussed and relevant results of completed tests are presented. In addition, the following points are stressed:

- objective of the wind tunnel tests,
- design of test installations,
- completed test programs,
- future aspects.

1. Introduction

Active Control Technology (ACT) can improve aircraft performance and operational capabilities. But, in order to obtain real benefits from ACT it must be considered as an integral element in the whole flight vehicle design approach. This means the traditional tradeoffs between aerodynamics, structures and propulsion have to be extended to include the capability of a full-time, full-authority fly-by-wire control system(1,2,3).

The possible applications of active control systems cover a broad range, from low-frequency flight dynamics up to high-frequency structural dynamics vibration. However, the use of ACT will require a detailed understanding of the anticipated external disturbances, aerodynamic and structural characteristics, control system responses and compatibility problems and will require considerable advances in the ability to describe and model such phenomena. Due to the close interrelationship between aerodynamical, flight-mechanical, aeroelastic, and control engineering problems, the development and testing of ACT call for methods allowing a comprehensive treatment of the subjects concerned.

Analytical investigations using *computer simulation* can give good results concerning the physical relationship in the dynamics of a complex system. However, computer simulation is often not sufficient because the effects and phenomena to be investigated are unknown and therefore not open to mathematical modelling. The disadvantages of inadequate mathematical models for computer simulation require experimental investigations to check the results of computer simulation.

Experiments are possible with both full-scale aircraft and models. There is no question that *flight testing* with full-scale aircraft is necessary to test active control systems. However, the increase in the complexity, cost, and risks of flight tests of advanced control concepts requires other methods for obtaining more experimental results.

Consequently *dynamic wind tunnel tests* are improved as an effective way for fundamental research in the field of ACT. The main advantages of this kind of simulation are: it is more realistic than computer simulation, less risky and relatively inexpensive compared with flight tests, and allows systematic tests under reproducable conditions.

A number of recent papers(4,5,6) have pointed out that this kind of wind tunnel test is required and that models can play an important role in the future development of control configured vehicles by providing data to verify analytical methods, thereby reducing the risks and cost of flight demonstration. Recent running dynamic wind tunnel programs with free flying and controllable models at NASA Langley Research Center(7), IMFL and ONERA(8), and MBB München(9) have demonstrated the efforts undertaken to satisfy the need for more experimental results for ACT.

Transferability of wind tunnel to full-scale results is the fundamental condition for dynamic wind tunnel experiments. To ensure transferability similarity of forces and motion between model and full-scale aircraft must be guaranteed. This will be achieved if the interference effects of wind tunnel facility on the model motion are small, and especially if the laws of similarity are satisfied. The laws of similarity are non-dimensional ratios of forces which, if held constant when passing from aircraft to model, will ensure similitude of the dynamic behaviour. "Buckingham's π-Theory" provides a technique to obtain the minimum number of independent non-dimensional ratios required. By using this technique, a generalized expression, which ensures similitude for a flexible body in an unsteady motion immersed in a viscous, compressible flow in a gravity field, can be written as(10)

$$\pi = f\{\mathrm{Re},\ \mathrm{Ma},\ \gamma,\ \mathrm{Str},\ \frac{p}{\rho V^2},\ \mathrm{Fr},\ \mu_L,\ \frac{E}{p},\ \frac{D\,\dot{\alpha}}{p\,l}\} \qquad (1)$$

Complete dynamic similarity exists between a geometrically similar aircraft and model when all the nondimensional parameters on the right hand side of Equ. (1) are the same for both model and aircraft. The terms of Equ. (1) are

Condition on the working fluid:

$\mathrm{Re} = \frac{\text{inertia forces}}{\text{viscous forces}}$ (Reynolds number)

$\mathrm{Ma} = \frac{\text{inertia forces}}{\text{compressibility forces}}$ (Mach number)

γ = ratio of specific heats

Time scaling:

Str = reduced frequency (Strouhal number)

Aerodynamic forces:

$\frac{p}{\rho V^2}$ = ratio of aerodynamic forces

Gravity considerations:

$\mathrm{Fr} = \frac{\text{inertia forces}}{\text{gravity forces}}$ (Froude number)

Body mass, stiffness and damping:

μ_L = relative mass parameter

$\frac{E}{p}$ = non-dimensional stiffness parameter

$\frac{D\,\dot{\alpha}}{p\,l}$ = non-dimensional damping parameter

Usually it is not possible to obtain exact similarity in wind tunnel experiments, i. e. to hold all the non-dimensional parameters constant when passing from aircraft to model. This is because of the inherent problem of capability in scaling for all parameters simultaneously (for example for Reynolds number, Mach number and Froude number).

For that reason one is forced to resort to approximate similarity. In that case the effect of the violation of a special scaling law on the experiment must be investigated. This leads to a choice of laws which are essential for the validity of the experiment and which therefore must be satisfied.

In view of this two facilities for dynamic model testing in wind tunnels have been constructed at the DFVLR:

- the "Installation for Dynamic Simulation in Wind Tunnels" for investigations in the field of fixed-wing aircraft and
- the "Rotor Test Stand" for investigations in the field of rotary-wing aircraft.

This paper describes both wind tunnel facilities and discusses problems of transferability of measurement data from model to full scale. Relevant results of completed tests are presented and future aspects are discussed.

2. Dynamic Model Testing for Fixed-Wing Aircraft

The design of future civil and military fixed-wing aircraft will be mainly influenced by the implementation of ACT in the design process. Some special applications of ACT which might be achieved in the next generation are(11):

1. Active Gust Alleviation:
   - for improvement of pilot and/or passenger comfort
   - for increase of aircraft life by reducing structural loads
2. Active Lift Distribution:
   - for fatigue reduction (maneuver load control)
   - for improvement of maneuverability (direct lift control)
3. (Limited) Artificial Stability:
   - for weight/drag reduction
4. Envelope Limiting:
   - for "carefree maneuvering"
5. Active Flutter Control:
   - for suppression of wing-store flutter

However, there is still a lack of knowledge of many aspects of the aerodynamic/aeroelastic/dynamic behaviour of the aircraft and consequently our ability to predict and improve aircraft characteristics by using ACT is limited at present. This applies particularly to flight mechanics, because it is the task of flight mechanics to investigate the interdisciplinary problems(2,12).

From the flight mechanics standpoint fundamental research is necessary or advanced development is required on topics such as

- Effect of conventional controls operating at high frequency on the dynamic behaviour of the aircraft.
- Effect of unconventional controls which are deployed in an unusual manner on the dynamic behaviour of the aircraft (i. e. canards, spoilers and unconventional flaps).
- Effect of active control systems on each other, i. e. the compatibility of ACT functions.

DFVLR is working, in cooperation with other institutions, on the solution of problems associated with the above-mentioned research areas.

At present, these basic investigations are concentrated on the determination of the effect of

- type and location of sensors and control surfaces
- control surface rate limitation
- nonlinear/nonstationary effects due to quick acting flaps
- measuring accuracy

on the performance of an active gust alleviation system. For the investigations DFVLR uses the Installation for Dynamic Simulation in Wind Tunnels together with a reduced-scale rigid model of the ZKP experimental aircraft Do 28 TNT as a test bed(13,14).

2.1 DFVLR-Installation for Dynamic Simulation in Wind Tunnels

The Installation for the Dynamic Simulation in Wind Tunnels is an extension of a similar test technique, which is used for testing flutter-models but allows the simulation of a part of the rigid body motion. The main parts of the installation are (Figure 1, 2):

- the suspension frame for the model
- the central control station
- the gust generator system
- the weight compensation system
- the model.

Suspension Frame

The suspension frame consists of a large tubular frame in combination with a vertical rod, which allows freedom of motion in pitch, yaw, heave and to some extent in roll. The frame surrounds the open test section of the 3 m-subsonic wind tunnel; the distance between frame and airflow is 0.5 m. The resonant frequency of the rod/frame system is about 14 Hz. This value is high enough to allow measurements up to frequencies of 10 Hz. The maximum pitch motion is ± 10 degrees, the model can heave ± 0.4 m.

Central Control Station

The central control station is located in a container next to the test section. This container houses the model control devices, the measurement data processor, and various monitoring devices.

Gust Generator System

Two movable flaps are installed into the nozzle of the wind tunnel. They are driven by an electro-hydraulic actuator. This device allows a deflection of the airflow within the test section of up to 10 degrees. The gust generator can generate gusts in the frequency range from zero to 15 Hz. It is possible to generate various types of gust profiles, such as impulsive or stochastic gusts. The properties of the gust generator allow the simulation of a scaled stochastic gust field with a special characteristic (for example Dryden).

Weight Compensation System

A servo controlled vertical force generator can produce constant vertical forces independent of the model motion. This device is necessary due to the laws of similarity and in order to control the model in the airflow.

Model

The type of model depends on the actual problem to be investigated. The models may have inertial and elastic scaled properties. For the present purpose a 1 : 8 scaled model of a small transport aircraft is used. This model is built from carbon fiber material, which results in an almost rigid structure (Figure 3). It is equipped with control surfaces (inner flaps, outer flaps, elevator) which are driven by fast acting servo actuators. Sensors such as accelerometers, rate gyros, pressure transducers, potentiometers for the control surfaces, various angle of attack probes are installed at different locations of the model to measure the motion and the disturbances. Power supply, control signals and measured data are transmitted to and from the model via cables.

2.2 Transferability of Wind Tunnel Test Data to Full Scale Fixed-Wing Aircraft

For a complete dynamic simulation Equ. (1) produces the following set of parameters which must be correct:

- Geometric Scaling
- Mach Number
- Reynolds Number
- Strouhal Number
- Froude Number
- Relative Mass Parameter.

The other parameters, such as ratio of specific heats, body stiffness and material damping, are satisfied automatically because the dynamic simulation uses the same medium "air" as in real flight and the model is a rigid model.

The requirement for constant ratio of aerodynamic forces is fulfilled using the aerodynamic forces in non-dimensional form derived from static wind tunnel tests which correspond to the value of the full-scale aircraft.

In the case of experiments taking aeroelasticity of structure into account, the number of non-dimensional mode shapes, essential for the experiment must be approximated.

Geometric Scaling

In order to achieve the same aerodynamic characteristics on a model as exist on the full-scale aircraft it is necessary for the aerodynamically important portions of the aircraft to be geometrically scaled. The maximum size of the three-dimensional model is determined by the size of the wind tunnel test section. The test section of the DFVLR subsonic wind tunnel used for the experiments has a diameter of 3 m; this yields a length scaling ratio of 1 : 8, model to aircraft.

Mach Number

The Mach number takes into account the compressibility effects of the airflow. In practice these effects can be neglected for Mach numbers below $Ma \approx 0.4$, as in this case of dynamic simulation.

Reynolds Number

The use of a down scaled model makes it impossible to simulate the Reynolds number correctly in wind tunnels using air only. This is only possible by using very high velocities, which, however, leads to problems with Mach number again. It is important to have the Reynolds number in wind tunnel tests higher than the critical Reynolds number when the airflow becomes turbulent. The dynamic wind tunnel tests at DFVLR are conducted with a Reynolds number of $0.53 \cdot 10^6$ which is close to the critical Reynolds number. However, static wind tunnel tests with different Reynolds numbers have shown that the Reynolds number has no important effect in the particular area being investigated. This is true especially as the dynamic tests only use an angle of attack of up to 5 degrees. Thus the high angle of attack region is avoided in which a reduction in maximum lift coefficient will occur and at which the moment curve will break if Reynolds number is reduced.

Mass and Mass Distribution

To ensure similar dynamic behaviour the relative mass parameter $\mu_L = 2\, m/\rho\, S\, l_\mu$ and the relative radius of inertia $k_y = (r_y/l_\mu)^2$ must be valid for both model and aircraft.

Strouhal Number

The Strouhal number, which corresponds to the reduced frequency $\omega\, l_\mu/V$, ensures equal dynamic angle of attack. Since the Strouhal number must be valid for both model and aircraft, the time scale factor can be determined for a given geometric scaling.

Froude Number

In dynamic processes gravity is of great importance, because the ratio between acceleration of motion and gravity acceleration must be constant. It is clear once the velocity and geometric scale factors have been established that it is often difficult to satisfy the requirements of the Froude number at the same time.

The significance of the Froude number as applied to airplanes is shown in(15): the combination of the Froude number with the relative mass parameter μ_L yields $\mu_L/Fr = m\, g/\rho\, S\, V^2 = C_{L_O}/2$, where C_{L_O} is the lift coefficient in the initial steady flight condition. This shows that the Froude number determines the steady flight condition. In order to carry out similar wind tunnel tests it is often necessary to change the gravitational field. This can be done in the DFVLR test facility by a weight compensation system which produces a constant additional vertical force on the model independently of the model motion.

Thus two types of simulation are possible in the DFVLR installation(16):

1. Froude scaled simulation
   The model flies without the vertical force generation in a state of natural gravity. All the lift has to be produced by the model itself.

2. Simulation with weight compensation
   The lift of the model is supported by a constant vertical force. This results in a reduction in the velocity needed to produce the required lift of the model.

Both types of simulation are conducted in the installation. For the investigations the simulation with weight compensation is preferred due to the better time scaling. In the special wind tunnel program with the Do 28 TNT model the weight compensation system has to create 28 % of the total lift to achieve the correct steady state conditions.

2.3 Test Specific Effects

The model suspension was chosen so as to allow the simulation of the longitudinal motion of an aircraft. Figure 4 shows that due to the vertical rod there are two additional forces K_x and K_z instead of thrust in the case of a free flying model. K_x represents the horizontal rod-force which compensates for the drag of the model. K_z is the artificial constant vertical force on the model, obtained by using the weight-compensation system to model the correct Froude number.

The equation of the longitudinal motion of a suspended model in comparison with the equation of a free-flying model shows that due to the blockage of the x-degree of freedom the phugoid motion is fully suppressed. The short period mode, however, is not affected significantly because the corresponding terms in the equations are small. Figure 5 shows the Bode plot of the response of the suspended model and the free-flying model due to an elevator input(16). There is a good agreement between the motion of both models for frequencies equal or higher than the short period mode. In this frequency range good transferability of the results can be obtained. At frequencies lower than half the short period mode frequency the suppressed phugoid mode results in major differences.

The wind tunnel experiments conducted show that due to the special suspension technique some additional influences exist which affect the movement of the model:

1. The cables for data transmission to and from the model create small forces and moments which are dependent on the heave of the model(17) (Figure 6).
2. Although it is outside the test section the large suspension frame produces a contraction of the airflow in the plane of the suspension frame, but leads to an expansion of the airflow behind the frame. This results in a gradient $\partial\alpha/\partial z$, which varies according to the position in the test section(17) (Figure 7).
3. The two-dimensional gust field which is produced by the gust generator shows a nonlinear propagation dependent on frequency and position(14) (Figure 8).

Thus the wind tunnel investigations began with extensive experiments for the identification of the model motion and all disturbing effects. The goal was to obtain a mathematical description which models all effects. Difficulties arose in arriving at a mathematical model of the gust field. But despite some deficiencies a good agreement now exists between the results of measured and computed gust field within the frequency range from 0.8 Hz to 5 Hz.

2.4 Wind Tunnel Test Programs

The Installation for Dynamic Simulation in Wind Tunnels was used in two experimental programs, which were conducted in the DFVLR 3 m subsonic wind tunnel. In the first program ride smoothing systems and elastic mode suppression systems for wing and fuselage bending modes were evaluated. In this program, which showed the application potential of the installation, a flexible combat-type multipurpose aircraft model was used(18).

The goal of the second program was to develop and test a gust alleviation system for the Do 28 TNT aircraft. The results of this program are given in(19).

The current investigations are concentrated on fundamental research associated with the application of active control technology. One main part is the identification and modelling of the effect of high frequency flap inputs, required for gust alleviation systems, on the dynamic behaviour of an aircraft. An example of these investigations will now be given.

For the investigation of aerodynamic effects due to high frequency inputs special tests are performed. Figure 9 shows the results of wind tunnel measurements in the case of quick acting flaps in comparison with results obtained by applying system identification methods (Maximum-Likelihood method) to the flight test data. To model the aerodynamic effects two types of mathematical model are used.

The first model is a linear model, which includes the pitching moment equation in the customary form

$$\ddot{\theta} = M_\alpha\,\alpha + M_q\,q + M_{\dot{\alpha}}\,\dot{\alpha} + M_\delta\,\delta \qquad (2)$$

This equation takes into account the effect of relatively low frequency changes of lift on the downwash at the elevator. The comparison of the identification results with the wind tunnel measurements shows discrepancies in the response of wind tunnel model and computer model (left side of Figure 9). This can be seen particularly in a time shift of the pitching motion.

It is evident that this mathematical model is not applicable in the case of high frequency or step inputs, which are required for active control systems such as gust alleviation systems because of some non-stationary wing-tail interference. To model this special effect another approach is used which takes into account directly the timelag from wing to tailplane. This produces a mathematical model, which includes the equation of the pitching moment in the form

$$\begin{aligned}\ddot{\theta} = {} & M_\alpha\,\alpha + M_q\,q + M_\delta\,\delta && \text{stationary part}\\ & \left.\begin{aligned} & - \varepsilon_{WE}\,M_{\alpha E}\,[\alpha(t) - \alpha(t - T_{WE})] \\ & - \varepsilon_{FE}\,M_{\alpha E}\,[\delta(t) - \delta(t - T_{WE})]\end{aligned}\right\} && \text{dyn. part} \qquad (3)\end{aligned}$$

with

$$\varepsilon_{WE} = \frac{\partial\alpha_E}{\partial\alpha_W}\ , \quad \varepsilon_{FE} = \frac{\partial\alpha_E}{\partial\delta}\quad .$$

The first term of the dynamic part of Equ. (3) describes the $\dot{\alpha}$-dependency of Equ. (2). The second term models the dynamic effect of quick flap deflection, i. e. the delay of the downwash effect between flap deflection and its influence on the elevator. The use of this model leads to a better curve fit in the pitching motion between measured and computed data (right side of Figure 9).

To make this effect clear Figure 10 shows a comparison of the outputs of two simulated models due to very high frequency input signals. From the curves it can be seen that for higher flap deflection rates the effects of the time lag of the downwash become important for the mathematical modelling.

This example shows that in the field of fixed-wing aircraft the dynamic simulation technique in combination with the system identification technique is a good tool for obtaining more information and data about the dynamic effects associated with the implementation of ACT.

3. Dynamic Model Testing for Rotary-Wing Aircraft

In recent years theoretical work in the helicopter field has been intensified. It is necessary now more than ever before to verify and expand theoretical results with proper and sufficient testing in order to obtain improvements for the design of new helicopter systems.

One major advance in rotorcraft design will be the introduction of active control technology (ACT). For design application of this technology many questions remain to be answered. Extensive wind tunnel testing will contribute to finding the desired high-quality solutions.

3.1 Active Control for Helicopters

Before the application of ACT is discussed, some flight mechanical problems of helicopters will be reviewed shortly. This seems to be necessary because the extensive integration of control, lift generation and forward thrust generation into one system, the rotor, leads to substantial differences in comparison with fixed-wing aircraft(21).

Helicopter Control Problems

The pilot's control of forces and moments at the rotor is performed usually by varying the rotor blade pitch angles by means of a mechanical or hydraulic system.

The relatively simple realization of the normally used monocyclic rotor control and the basic fulfillment of helicopter trim and control requirements make the problems connected with this system appear less significant in the past.

In Figure 11 the basic flight mechanical deficiencies of helicopters using conventional control systems are shown:

- The basic helicopter is inherently unstable, longitudinally and laterally, particularly at high forward flight speed.
- To a greater or lesser extent, the helicopter's controls are coupled and the magnitude of these couplings varies with flight conditions.
- The vibrations transferred from rotor to fuselage in specific speed ranges exceed the standard which is reasonable for passengers and jeopardize the mission performance.
- The maximum thrust levels obtainable and therefore the stationary load factors decrease as forward speed increases, which leads to the design of the rotor being determined essentially by high speed considerations and to the rotor having surplus capacity at low speed.

These flight mechanical problem areas are caused essentially by the aerodynamic and dynamic conditions at the rotor. For that reason major improvements in the helicopter dynamics, including eigen-, disturbance-, and control-response, can only start at the rotor.

Objectives of Active Rotor Control

Even in normal flight conditions, but especially near the boundary of the flight envelope, the helicopter rotor must operate in a severe aerodynamic/dynamic environment. This includes

- stalled and reversed flow on the retreating blade,
- transient Mach number effects on the advancing blade,
- atmospheric turbulence,
- impulsive flow due to blade-vortex interaction,
- blade-fuselage interference flow,
- rotor instabilities,
- blade aerodynamic and/or dynamic mismatch.

The conventional monocyclic rotor control is unable to avoid these effects or to reduce the consequences, because the control angles of the individual rotor blades are completely determined by the flight condition and coupled with each other.

The solution consists in sensing instantaneous rotor behaviour and acting by means of additional or new controls to alleviate the disadvantageous effects caused by the above-mentioned rotor environment. The answer is active rotor control(22).

In recent papers the objectives of the application of ACT principles for helicopters have been pointed out$^{(22,23,24)}$; among these are

- reduction of rotor vibrations, blade stresses and control loads,
- improvement of performance, helicopter ride qualities and helicopter handling qualities.

In this way it seems possible to alleviate substantially the flight mechanical problems of helicopters and to expand the flight envelope considerably.

Realization of ACT

At least two conditions must be satisfied in order to implement active control for helicopters

- the limitations of the present swashplate that couples the blade pitch angles and provides only monocyclic pitch variation must be overcome,
- the conventional mechanical/hydraulic linkages between the pilot's control and the rotor blade must be supplemented or replaced by electrical/optical signalling, making possible the extensive application of feedback techniques.

In order to realize all the benefits that active control can bring to helicopters, a concept involving individual blade control using extremely fast-response actuators combined with a full fly-by-wire/light system is envisaged. The technology for doing this is not available today.

In Figure 12 several steps are outlined in the development from the conventional helicopter to an ACT helicopter. Flight demonstration of helicopter FBW systems has, in fact, already been undertaken in the US and in Europe; other systems showing great promise are under development$^{(25,26)}$.

In the area of rotor control the R and D activities have been concentrated on the realization of higher harmonic rotor control as a first step towards active rotor control.

The principle of higher harmonic rotor control is presented in Figure 13. By dynamic adjustment of the swashplate a blade pitch angle is generated which is tuned in amplitude and phase and which will be superposed to the pitch angle of the conventional control. In $^{(23)}$ additional rotor types are presented utilizing higher harmonic control.

All experimental programs known so far in the area of higher harmonic control have been conducted in wind tunnels, investigating first of all the question of reducing the rotor induced vibrations $^{(27,28,29)}$. In particular, problems of reliability and safety of flight requirements have prevented up to now the development of a flightworthy active control system. In $^{(30)}$ preliminary design studies are presented for selecting a higher harmonic blade pitch control system for flight testing on a helicopter.

3.2 Transferability of Model Test Data to Full-Scale Helicopters, Model Similitude

The transferability of test data is dependent on the proper usage of the model scaling laws. Additionally other factors such as wind tunnel interference effects must be considered$^{(31,32)}$.

Starting from Equ. (1), the significance of particular similarity parameters will be discussed, especially with regard to the application of ACT.

For a complete simulation which takes into account a flexible rotor in a viscous, compressible flow in a gravity field, the following parameters must remain constant.

- Ratio of linear dimensions l_{FS}/l_M
- Mach number

$$Ma = \left(\frac{\text{inertia forces}}{\text{compressibility forces}}\right)^{1/2}$$

- Reynolds number

$$Re = \frac{\text{inertia forces}}{\text{viscous forces}}$$

- Froude number

$$Fr = \frac{\text{inertia forces}}{\text{gravity forces}}$$

- Density ratio

$$\frac{\rho_s}{\rho} = \frac{\text{structural density}}{\text{fluid density}}$$

- Elasticity ratio

$$\frac{E}{\rho\, V^2} = \frac{\text{structural elasticity}}{\text{fluid compressibility}}$$

Additionally it is supposed that only wind tunnels utilizing air at atmospheric pressure are available.

It is possible to define different sets of similarity parameters for a complete rotor simulation. The decision for this set was influenced by the specific problems which have to be investigated as well as by the clarity of these parameters$^{(33)}$.

Ratio of Linear Dimensions

The "geometrically scaling" approach is popular for rotors because of a number of factors, one of these being that, if everything is geometrically scaled, the material can be the same as in full-scale and the stresses will be the same.

It is usually possible to reduce the external shape of a rotor by applying the same scale factor. Unfortunately the reduction of all full-scale dimensions by the same scale factor often brings fabrication and handling problems because of the decreased absolute thickness of many parts and the small absolute size of others. The geometrically scaling approach will be practicable for a large model rotor.

Mach Number

Compressibility effects on airfoil section characteristics are very extensive especially at the high subsonic Mach numbers encountered in the very important outboard regions of rotor blades.

As pointed out in the preceding sections, the effects of the unfavourable rotor characteristics which have to be reduced by active control are caused by aerodynamic influences to a great extent.

Thus correct simulation of Mach number is a prerequisite for aerodynamic accuracy for rotor tests especially when active control technology is included. "Mach scaling" naturally implies a model tip speed the same as full-scale and a wind tunnel capable of covering the whole full-scale flight speed range.

Reynolds Number

The use of a Mach scaled model rotor makes impossible the correct simulation of Reynolds number in wind tunnels using air. For rotary-wing aerodynamics a number of papers(34,35) have shown that the trends in $c_{L\max}$, Reynolds number, and Mach number produce a considerably more favourable model/full-scale relationship than for fixed-wing aircraft.

Although Reynolds number considerations are important, particularly for higher advance ratios ($\mu > 0.5$), it is much more important to properly simulate the Mach number. Of course, this approach is a correct one for a large model rotor.

Froude Number

The Froude number also cannot be simulated correctly with a Mach scaled model rotor. Generally the Froude number is too large. For rotors with a substantially horizontal disc plane, the gravitational forces on a rotating blade have a constant value in the flapwise direction. Since the flapwise aerodynamic, centrifugal, and inertia forces are usually large compared to the blade weight, the gravitational forces can be ignored.

Density Ratio and Elasticity Ratio

In order to ensure similar dynamic characteristics with a Mach scaled model rotor, the structural density and the modulus of elasticity should be identical to the full-scale values. Geometrically scaling using the same materials is an obvious method of ensuring dynamic similarity. In this case the rotor blade natural frequency ratios and the stresses in the rotor system are the same as full-scale.

For relatively large model rotors, this method of model fabrication is practicable.

The discussion of these conflicting model scaling laws results in the following demands with regard to ACT applications for model rotors:

- For a great many tests Mach scaled models are required,
- the rotor models have to be designed as large as possible, taking into consideration the wind tunnels available.

Up to now in Germany there have been two wind tunnels suitable for experiments with large rotor models. One is at the Volkswagen (VW) research facility in Wolfsburg, having a 7 m by 5 m test section and a 50 m/sec maximum test section wind speed. The other is at the Daimler-Benz (DB) facility in Stuttgart with a 7.4 m by 4.9 m test section and a 80 m/sec maximum test section wind speed. Now a third wind tunnel is available, specially designed or at least very suitable for V/STOL, helicopter, and rotor testing: the German-Dutch Wind Tunnel DNW. This new and most advanced low speed tunnel in Europe features four interchangeable test sections up to 9.5 m by 9.5 m cross-section, and air speeds up to 150 m/sec(36). This wind tunnel will be the prime candidate for future tests with large rotor models.

3.3 DFVLR-Rotor Test Stand

In the DFVLR Institute for Flight Mechanics a rotor test stand for testing in large wind tunnels has been assembled in a joint program with German aircraft industries under contract by the German Ministry of Defence.

Since the start of operations in 1976 several test programs have been carried out and the test techniques have been improved continually(37,38). In the last year the possibility for high-frequency dynamic control of the rotor was provided by extensive hardware modifications. With this, an essential prerequisite was fulfilled for the experimental application of active control principles to the model.

Design Requirements

From the beginning the versatility of the test equipment had to be considered. The test stand must be adaptable to many different investigations in the fields of aerodynamics and dynamics, and the transferability of test results to full-scale helicopters must be valid for these investigations.

In addition, the test stand should be suitable for different rotor models such as shaft driven and reaction driven rotor systems, and the test stand should be adaptable to different fuselage, tail, and tail rotor configurations.

Finally, the test stand should fit in the large wind tunnels available. The answer to these requirements was a Mach scaled model, having a maximum rotor diameter of 4 meters.

Hardware Realization

The test stand hardware is shown in the Figures 14 and 15.

At present two Mach scaled model rotors are available:

- a hingeless four blade shaft driven rotor, and
- a two-bladed see-saw rotor which can be either shaft or reaction driven.

For the application of ACT the hingeless rotor model is the prime candidate. This rotor has soft flapwise and soft inplane blades, the hub is stiff flapwise and stiff inplane. In the design of the scaled rotor care was taken to model the stiffness and mass distribution of the MBB BO 105 main rotor accurately. With only a few exceptions, the dimensions and wall thickness were scaled linearly. The blades are fiberglass and the hub is steel. The following Table gives some important characteristics of the rotor:

Diameter	$D = 4$ m
Number of blades	$z = 4$
Solidity	$\sigma_{0.7} = 7.73$ %
Blade planform	rectangular
Blade profile	NACA 23012
Tip speed	$U = 220$ m/sec
Flapping frequency ratio	$\omega_\beta/\Omega = 1.12$
Lagging frequency ratio	$\omega_\zeta/\Omega = 0.71$
Design thrust	$T = 3630$ N
Maximum thrust in hover	$T_{max} = 4400$ N

For rotor control a swashplate system is used. The non-rotating part of the swashplate is moved by three electro-hydraulic actuators, adjusting both collective and cyclic blade pitch angles and in addition moving the swashplate dynamically.

The actuators are remotely controlled and are designed for high-frequency response up to more than 80 Hz, having a dynamic amplitude of ± 3 mm. The actuator's phase shift is roughly 1 degree/Hz, its performance is unaffected by the dynamic swashplate loads. For driving the actuators a hydraulic system with a power installation of about 30 kW is necessary. In this way it is possible to vary the blade pitch up to six times the rotor rotational frequency Ω.

Thus it is possible to realize higher harmonic rotor control as a first step towards active rotor control.

In order to adjust the rotor's angle of attack the rotor shaft angle is controlled by tilting the upper part of the test stand.

The drive system of the rotor consists of a high power (90 kW at 1050 RPM) compact hydraulic motor which is installed in the test stand. The bulky primary power unit, which is the electric motor and hydraulic pump, is connected to the hydraulic motor with high pressure hoses. Special flex-couplings have been designed and fabricated to have the required torque capability, but these are still "soft" enough so that axial force, lateral force, and moment losses to the test stand are very small compared to the loads measured.

In order to measure the forces and moments at the rotor hub and at the fuselage, which can be attached if required, two six-component strain gage balances have been installed. These balances measure the steady-state loads with good accuracy (error < 2 % of maximum load); they also provide dynamic load data up to 4 per revolution.

Because the forces and moments of the rotor are measured independently of the fuselage loads, interference effects between rotor and fuselage can be identified. RPM, torque, and rotor power are obtained from a measurement package fitted in the drive shaft.

Generally it is necessary to obtain data from the rotor concerning blade motion, blade loads and other variables. Data from the rotor is transmitted to the stationary test stand by a PCM-system. Thirty-two channels are provided, each with a frequency response up to 100 Hz.

The dynamic data system, Figure 16, was designed for various tasks:

- Collecting all the data measured in the non-rotating as well as in the rotating elements of the test stand. This data is recorded on magnetic tape for detailed off-line analysis of the experiments.
- Providing quick-look data, which makes it possible to control the model and to make timely decisions while experiments are being run.
- Realizing feed-back control of the rotor and automatic monitoring of the experiments.

These tasks, which present especial difficulty in the case of active control applications, will be accomplished by digital and analog computers as well as by a frequency analyser and additional peripheral equipment.

Model Preparing for Wind Tunnel Tests

The complex hardware as well as the extensive software which is necessary for carrying out wind tunnel tests with model rotors including ACT forces the experimentators to prepare their test equipment carefully before starting wind tunnel tests. This step, which demands far more time than that required for measuring in the wind tunnel, becomes especially important when using large models. A badly prepared model not only produces no data or useless data but in addition the safety of the model will be jeopardized to a great extent.

If the high cost of model production and wind tunnel operation is considered, the urgency of an extensive model preparation phase will become clear.

The following steps are especially important in this phase:

- Hardware running tests,
- static and dynamic sensor calibration,
- software checking, and
- securing of functional data flow.

For the acceleration of this phase, which contains numerous recurring individual steps, the application of computers to model preparation has been started. In particular, the area of functional checks and sensor calibrations will be a good starting point for this.

3.4 Results of Completed Test Programs

During the first tests with the four-bladed model rotor, the following tasks were carried out:

- Measurement of rotor characteristics,
- definition of regions of flight safety,
- investigation of aerodynamic interference effects between rotor and fuselage,
- measurement of rotor downwash, and
- measurements for the comparison of dynamic model rotor loads with results from full-scale flight tests.

Figure 17 shows typical results(39). The data were obtained in the Daimler-Benz (DB) wind tunnel as well as in the German-Dutch Wind Tunnel (DNW). The comparison between model and full-scale shows the data points to be in good agreement, especially in the medium speed range.

The measurement data showing the 4/Rev. pitching moment coefficient appear to differ widely in the low speed range, and (not shown in Figure 17) in the high speed range. For the discussion of these differences the following points have to be considered:

- In-flight measurements are difficult at low speed,
- the high-frequency data have small absolute amplitudes,
- wind tunnel interference will be a limiting factor at low speeds, and
- Reynolds number effects at high speeds have to be taken into account.

In Figure 18 wind tunnel effects and Reynolds number effects are presented with respect to the transferability of rotor thrust data. Whereas in the low speed range the transferability is limited by flow breakdown onset, in the high speed range the flow separation onset is the limiting factor for transferability. These effects have to be considered in particular when dynamic data are being collected.

The results presented here demonstrate that the DFVLR-Rotor Test Stand is suitable for producing and measuring dynamic data. This test equipment is therefore an appropriate tool for providing substantial contributions to the application of active control systems to helicopters.

4. Conclusions and Future Activities

In this paper the DFVLR technique of dynamic model testing for active controls research is presented. The following conclusions can be drawn:

- ACT will improve performance and operational capabilities of fixed-wing as well as rotary-wing aircraft.
- Dynamic model testing can play an important role in the future implementations of ACT.
- The DFVLR test facilities
  - "Installation for Dynamic Simulation in Wind Tunnels" for fixed-wing aircraft, and
  - "Rotor Test Stand" for rotary-wing aircraft

  have been proved to be suitable tools for the investigation of flight mechanical problems connected with ACT.
- Wind tunnel results show that the transferability of dynamic model data to full-scale data is feasible in areas which are of major interest in the development of ACT systems.

Future DFVLR activities with regard to ACT include:

- Specific active control systems will be designed and optimized using the dynamic model testing technique.
- The transferability of model data to full-scale data will be demonstrated in further flight test programs.

- System identification techniques will be applied to the dynamic effects of lifting and control surfaces.
- Compatibility problems of active control systems will be investigated.
- The DFVLR dynamic model testing technique will be implemented in the German-Dutch Wind Tunnel (DNW).

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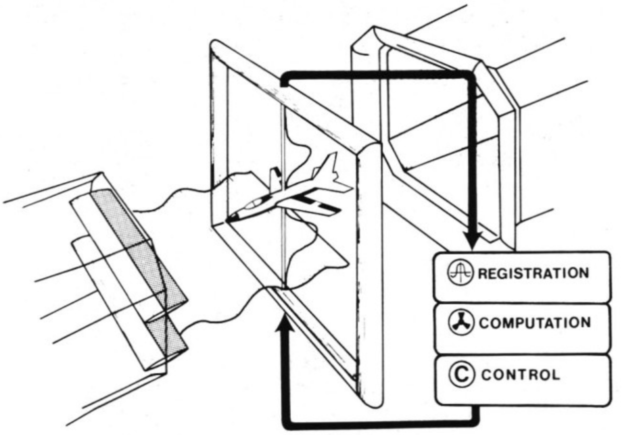


Figure 1. General View of the Installation for Dynamic Simulation in Wind Tunnels

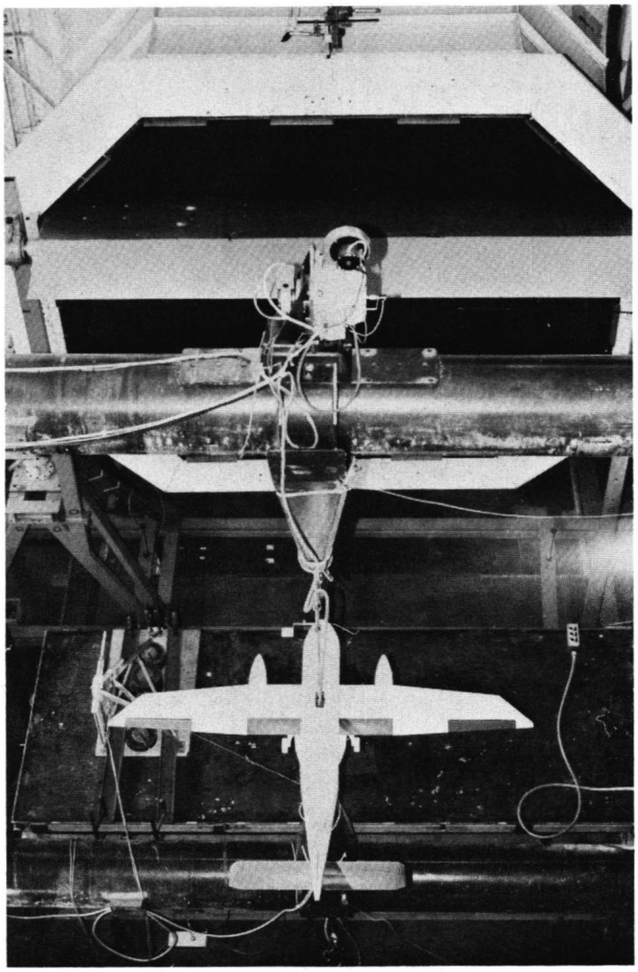


Figure 2. The Installation for Dynamic Simulation in the 3 m Subsonic Wind Tunnel

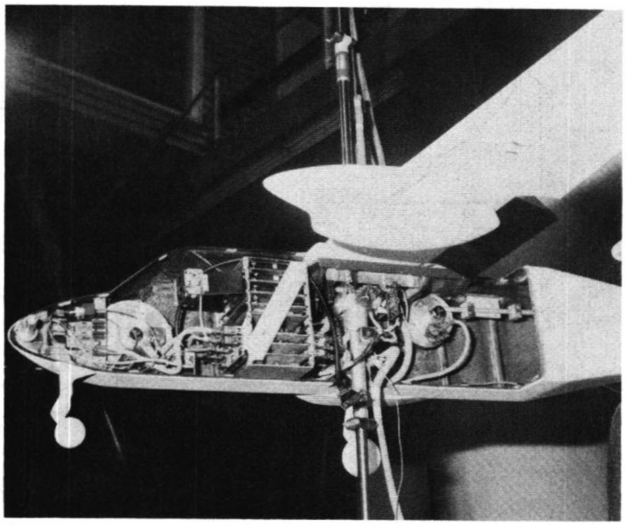


Figure 3. Remotely Controlled Wind Tunnel Model of the Do 28 TNT

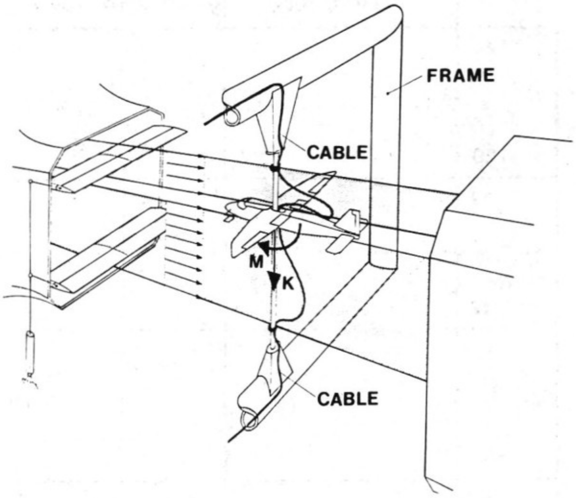
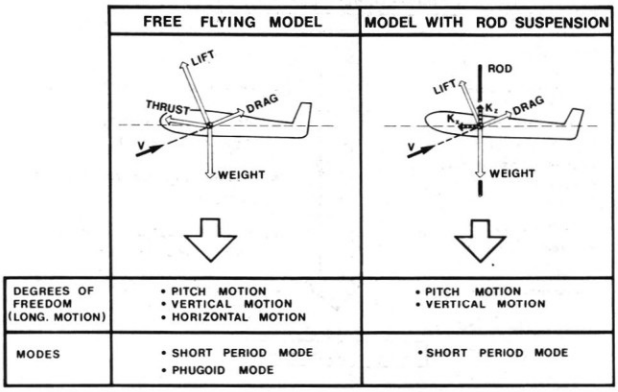


Figure 6. Disturbing Influence of Cables



	FREE FLYING MODEL	MODEL WITH ROD SUSPENSION
DEGREES OF FREEDOM (LONG. MOTION)	• PITCH MOTION • VERTICAL MOTION • HORIZONTAL MOTION	• PITCH MOTION • VERTICAL MOTION
MODES	• SHORT PERIOD MODE • PHUGOID MODE	• SHORT PERIOD MODE

Figure 4. Effect of Vertical Rod Suspension on Model Motion

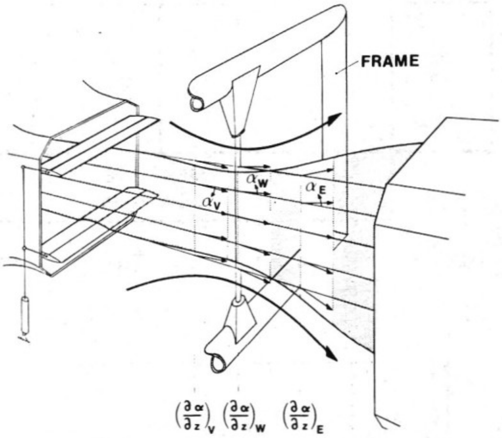


Figure 7. Suspension - Frame Interaction with Airflow

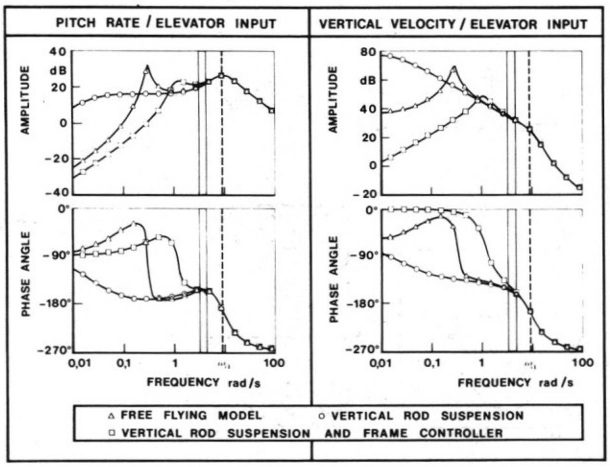


Figure 5. Frequency Response (Bode Plots) of Pitch Rate and Vertical Velocity to Elevator Input

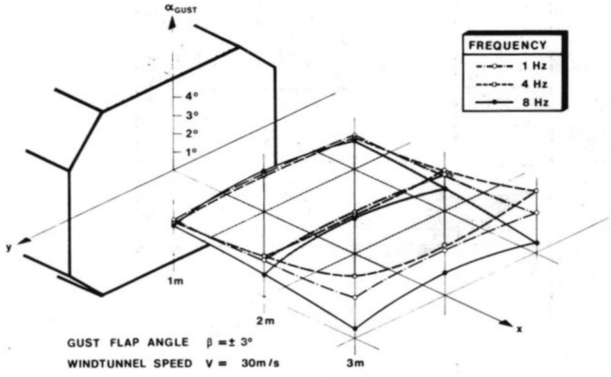


Figure 8. Gust Angle of Attack for Three Different Frequencies

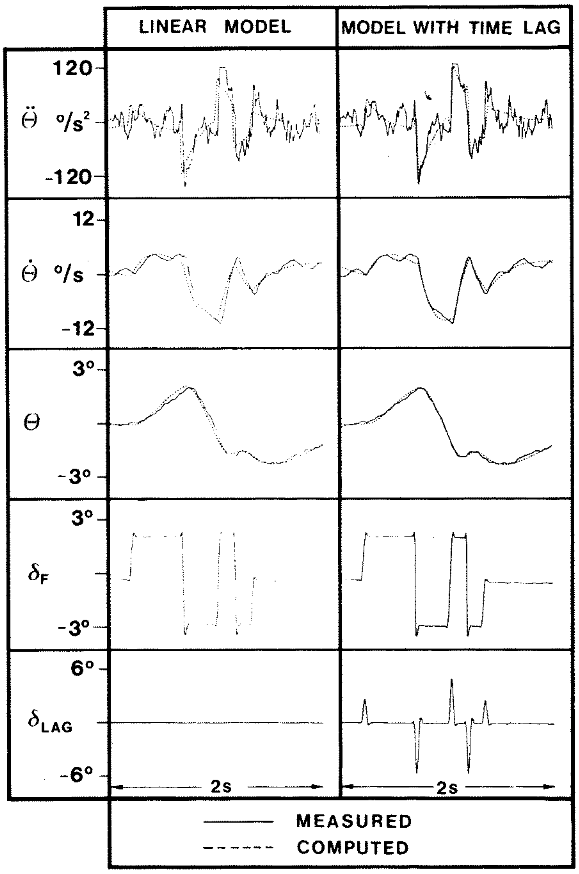


Figure 9. Problem of Wing-Tail Interference Modelling
$\delta_{LAG} = \delta(t) - \delta(t - T_{WE})$

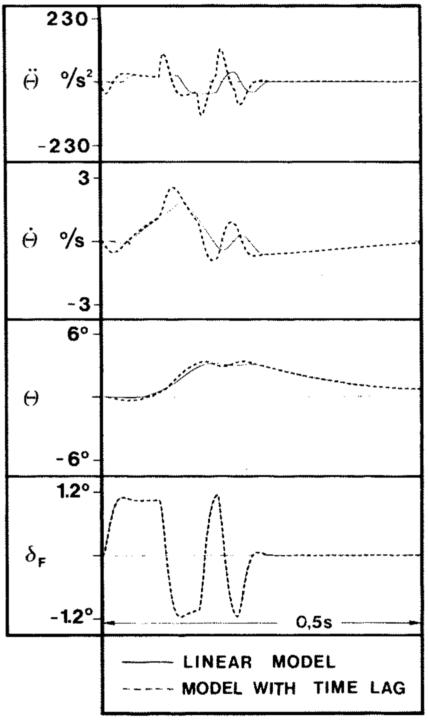


Figure 10. Influence of Time Lag on Simulation Results

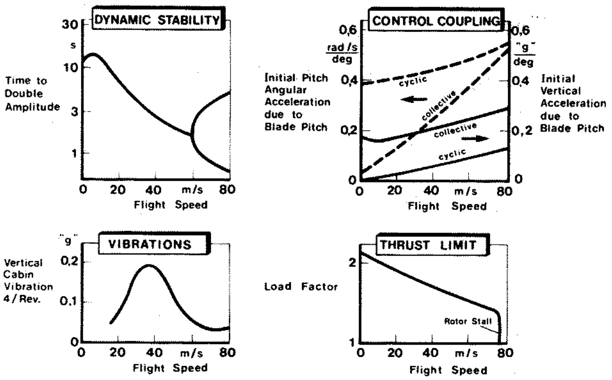


Figure 11. Problems of Helicopter Flight Mechanics

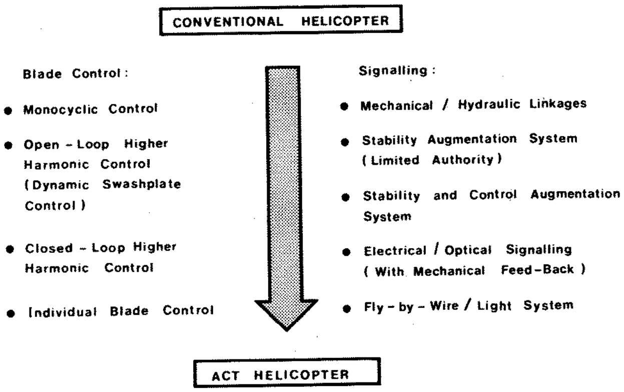


Figure 12. Active Control for Helicopters

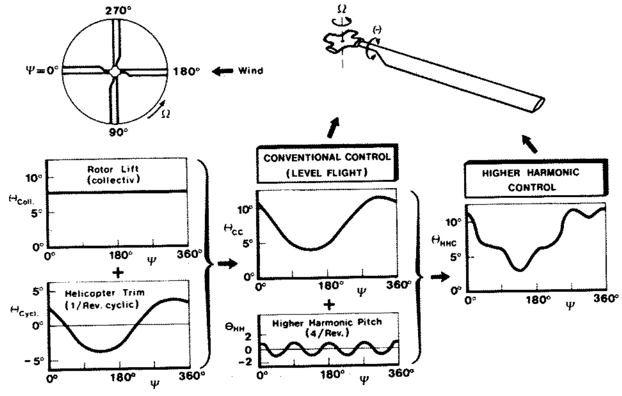


Figure 13. Higher Harmonic Rotor Control (Full Blade Feathering)

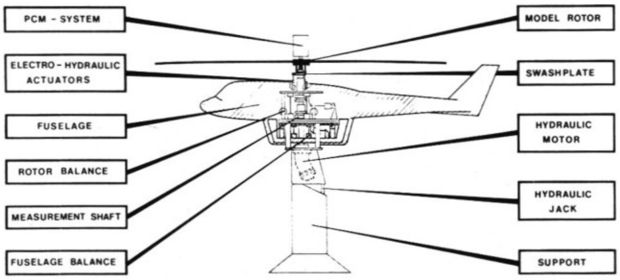


Figure 14. DFVLR-Rotor Test Stand

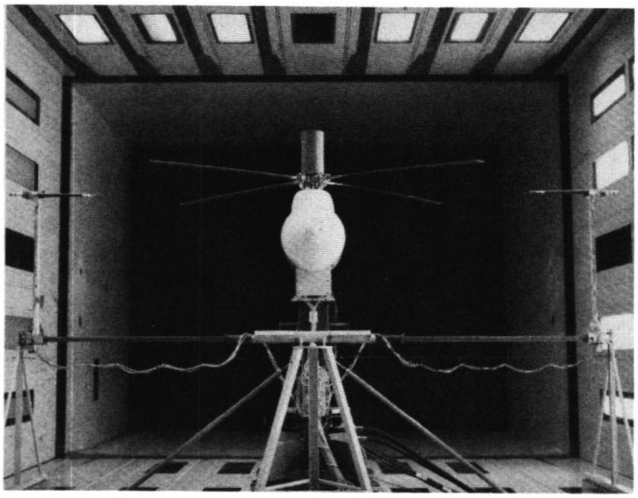


Figure 15. Rotor Test Stand in German-Dutch Wind Tunnel DNW

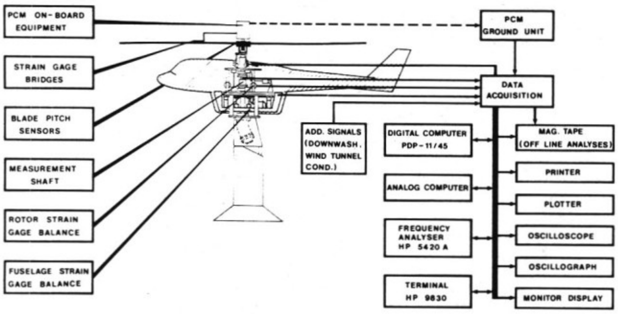
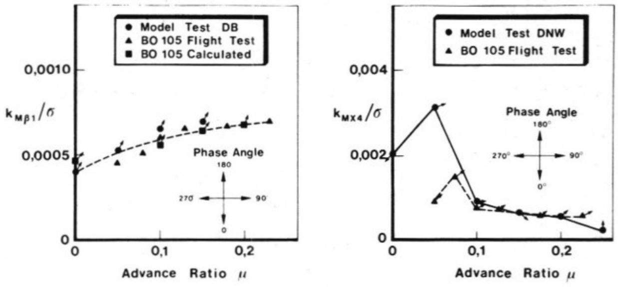


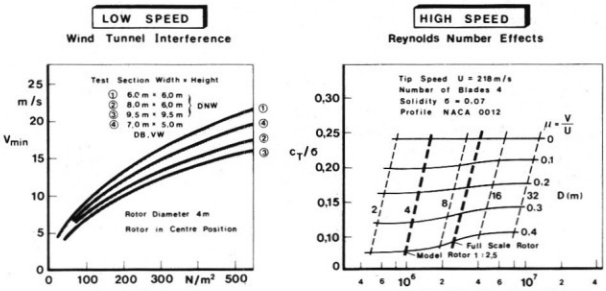
Figure 16. Dynamic Data System



1/Rev. Flapwise Blade Bending Moment Coefficient

4/Rev. Pitching Moment Coefficient

Figure 17. Dynamic Test Data (Comparison Model/Full-Scale)



Minimum Allowable Wind Speed V_{min} for Flow Breakdown Onset

Rotor Thrust Coefficient c_T/σ for Flow Separation Onset

Figure 18. Limits of Test Data Transferability