A RECONSTRUCTION METHOD FOR DETERMINING SPANWISE AIR LOADS FROM MEASURED STRUCTURAL RESPONSES

Dipl.-Ing. H.W. Lindert
Prof. Dr.-Ing. Dr. h.c. (H) H. Öry
Institut für Leichtbau, RWTH Aachen, FRG

Abstract

A method for determining rotor blade spanwise air loads from measured structural responses, such as bending moments, deflections, accelerations or a combination of these, is presented. A short introduction of the method and a brief summary of its basic equations is given. In general the method consists of an inverse solution of the rotor blade differential equation of motion on the complex phase plane and requires knowledge of the rotor blades structural and dynamical parameters. The method has been verified extensivly with response data aquired from wind tunnel model rotor tests and flight tests performed with Kamov-26 and MD Hughes 500 helicopters. Some typical reconstruction results from wind tunnel and flight test data are presented in the last part of the paper. In some of them, distinct blade vortex interactions are recognizable. The proposed reconstruction method has proven itself as a feasible, inexpensive and easy to use alternative to pressure measurement based, air load determinating methods.

List of Symbols

c, **C**	damping, damping matrix
D	dynamic matrix = **EM**
E	elasticity matrix
h, **h**	normal coordinate, normal coordinate vector
k, **K**	stiffness, stiffness matrix = E^{-1}
m, **M**	mass, mass matrix
M, $\overline{M}$	moment; modal moment
M̃	measured moment vector
p, **p**	force, force vector
y, **Y**	blade deformation, blade deformation vector
η	eigenmode vector
Φ	modal matrix
ζ, ζ	LEHR-damping factor, damping factor matrix
ω, ω	eigenfrequency; eigenfrequency diagonal matrix
Δ**x**	geometric lever matrix

indices

dyn	dynamic
el	elastic
gen	generalized
qs	quasi-static
recon.	reconstructed
t	time dependant
0	non rotating
Ω	rotating

Introduction

The standard method for determining air loads on wings or rotor blades, is to perform pressure measurements on the profile surface, and to compute the air loads from the pressure data using mathematical formulas and empirical profile coefficients. This is in effect an indirect method requiring several complex steps and prone to faulty results. A direct measurement of the acting air loads would obviously be the best method but is yet not feasible. Structural responses of the wing to the air loading, on the other hand, are relatively easily measured.

An arbitrary force acting on an ideal cantilever beam creates an unique beam deflection, dependent on the force magnitude, the beam elastic properties and the geometric beam dimensions. Given the elastic properties, the force quantity and the force location on the beam, the resulting deflection can be computed. This is called solving a direct problem (input --> output). Solving for the unknown force from the measured deflection, on the other hand, is called an inverse problem or also the reconstruction problem (output --> input).

At the Institute of Lightweight Aerospace Structures at the University of Technology in Aachen (RWTH Aachen) a method for determining the acting air loads from measured structural rotor blade responses has been developed. In accordance to the above said, the method was nominated the ***reconstruction method***

(RM). Response data may consist of local moments, deformations, accelerations or a combination of these. With the known rotor blade structural parameters, as there are the stiffness or elasticity matrix, the natural eigenfrequencies, damping and the mass distribution, the local air forces on the rotating rotor blade can be determined from the measured response data.

Extensive wind tunnel testing with model rotor blades yielded a vast amount of response data for evaluation with the RM. Reconstructed local air force distributions correspond very well to theoretical and measured air load distributions. The evaluation results encouraged flight testing with helicopters, which was performed in 1989, 1990, 1991 and 1993 in Budapest, Hungary. A russian built Kamov-26 and a MD Hughes 500 helicopter were flown during the tests. Evaluation of the in flight measured rotor blade responses with the RM showed very good results. In some evaluations of wind tunnel and MD Hughes 500 helicopter flight test data, distinct blade vortex interactions (bvi) were reconstructed in the rotor blade air loads.

Basic equations of the RM

Extensive descriptions of the mathematical equations, belonging to the rotor blade reconstruction method, have already been given in several publications (5)(6)(7)(14)(16), thus only a brief overview is given here. In general the RM is an invers solution of the equation of motion for the rotating rotor blade. The here regarded degree of freedom is the blade motion perpendicular to the rotor plane, meaning the flaping motion. A generalization of the equation of motion leads to a set of uncoupled, modal, differential equations describing SDOF systems. These equations can be solved on the complex phase plane using phase plane geometrical relations and the measured structural responses. A modal analysis of the rotor blade and the exact knowledge of the blade structural parameters is herefor required.

Rotating rotor blades resemble in their dynamical properties slender beamlike structures subjected to heavy centrifugal loading. The rotor blade is modelled as an one-dimensional, slender, linear elastic beam with lumped masses and proportional damping. Elastic blade properties are given bei the stiffness matrix $\mathbf{K}$, respectively the elasticity matrix $\mathbf{E}$. The dynamical rotor blade properties are described by the dynamical matrix $\mathbf{D} = \mathbf{EM}$. Let the rotating rotor blade be excited by a set of unknown external forces $\mathbf{p}_{(t)}$. The coupled set of equations of motion describing the blade deflection $\mathbf{y}_{(t)}$ perpendicular to the rotor plane is

$$\boldsymbol{M}\ddot{\boldsymbol{y}}_{(t)} + \boldsymbol{C}\dot{\boldsymbol{y}}_{(t)} + \boldsymbol{K}\boldsymbol{y}_{(t)} = \boldsymbol{p}_{(t)} \tag{1}$$

Generalization of eq.(1) yields a set of uncoupled differential equations. Herefor, the blade deflection $\mathbf{y}_{(t)}$ in eq.(1) is substituted by a linear superposition of the blade natural eigenmodes η.

$$\begin{aligned} \boldsymbol{y} &= \sum_{j=1}^{n} \boldsymbol{\eta}_j \boldsymbol{h}_j = \boldsymbol{\Phi}\boldsymbol{h} \\ \dot{\boldsymbol{y}} &= \sum_{j=1}^{n} \boldsymbol{\eta}_j \dot{\boldsymbol{h}}_j = \boldsymbol{\Phi}\dot{\boldsymbol{h}} \\ \ddot{\boldsymbol{y}} &= \sum_{j=1}^{n} \boldsymbol{\eta}_j \ddot{\boldsymbol{h}}_j = \boldsymbol{\Phi}\ddot{\boldsymbol{h}} \end{aligned} \tag{2}$$

$\mathbf{\Phi}$ is the modal matrix containing the rotating blade natural eigenmodes. Substituting eq.(2) in eq.(1) and multiplying from the left with $\mathbf{\Phi}^T$ gives the generalized equation of motion as

$$\boldsymbol{M}_{gen}\ddot{\boldsymbol{h}} + \boldsymbol{C}_{gen}\dot{\boldsymbol{h}} + \boldsymbol{K}_{gen}\boldsymbol{h} = \boldsymbol{p}_{gen} \tag{3}$$

with the generalized quantities defined as

$$\begin{aligned} \boldsymbol{\Phi}^T\boldsymbol{M}\,\boldsymbol{\Phi} &= \boldsymbol{M}_{gen} \\ \boldsymbol{\Phi}^T\boldsymbol{C}\,\boldsymbol{\Phi} &= \boldsymbol{C}_{gen} \\ \boldsymbol{\Phi}^T\boldsymbol{K}\,\boldsymbol{\Phi} &= \boldsymbol{K}_{gen} \\ \boldsymbol{p}\,\boldsymbol{\Phi} &= \boldsymbol{p}_{gen}\ . \end{aligned} \tag{4}$$

Equation (3) consists of j modal differential equations each describing a SDOF-System related to one of the rotor blade natural eigenmodes η_j.

$$\begin{gathered} \frac{1}{\omega_j^2}\ddot{h}_j + \left(\frac{2\,\zeta_{gen_j}}{\omega_j}\right)\dot{h}_j + h_j = \left(\frac{p_{gen_j}}{k_{gen_j}}\right) \\ \textit{with}\ \left(\frac{c_{gen_j}}{k_{gen_j}}\right) = \left(\frac{2\,\zeta_{gen_j}}{\omega_j}\right) \end{gathered} \tag{5}$$

The equation of motion for a proportionally damped SDOF-System can be solved "graphically" on the complex phase plane if the initial conditions are known. This method is well known and yields excellent results if the regarded time intervalls are accordingly small enough.

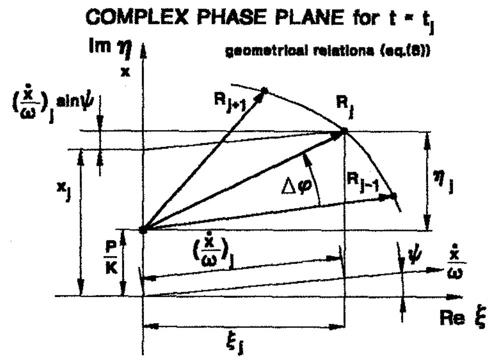


Fig.1 Geometrical relations on the complex phase plane for a SDOF-system. The exciting force p is constant during a time intervall 2Δt.

Lets regard the motion of a SDOF-System on the complex phase plane during a short time intervall 2Δt (Fig.1). Let the acting force p be constant during this time interval, x be the mass displacement and R the complex position vector of the oscillating mass. From geometrical relations in Fig.1, a formula for the force p_j at the time instance t_j can be derived.

$$\frac{\chi x_{(j-1)} - 2\cos(\Delta\varphi)\, x_{(j)} + \frac{1}{\chi} x_{(j+1)}}{\chi - 2\cos(\Delta\varphi) + \frac{1}{\chi}} = \left(\frac{p}{k}\right)_j \qquad (6)$$

$$with \quad \chi = e^{-\zeta\omega\Delta t} \; ; \quad \Delta\varphi = \omega\sqrt{1-\zeta^2}\,\Delta t$$

Accordingly, eq.(5) can now be solved on the complex phase plane by substituting h for x in eq.(6). For each natural blade eigenmode, a generalized force $(p/k)_{(t)}$ is thus computable. The generalized coordinates h_j of the SDOF-systems are determined from the measured structural responses according to eq.(7), whereby for different response types the appropriate modal quantitites must be inserted in the modal matrix

$$\begin{Bmatrix} h_1 \\ h_2 \\ h_3 \end{Bmatrix} = \begin{bmatrix} \eta_{11} & \eta_{12} & \eta_{13} \\ \eta_{21} & \eta_{22} & \eta_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix}^{-1} \begin{Bmatrix} \ddot{y} \\ y \\ M \end{Bmatrix} \qquad (7)$$

Modal reconstruction

The computed generalized forces $(p/k)_{gen}$ can be transformed to the sought air forces according to eq.(8).

response type	modal quantity type
bending moment; torsional moment	unit modal bending moment; unit modal torsional moment
blade deformation; blade deflection	rotating blade natural eigenmode
acceleration	rotating blade natural eigenmode

Table 1

$$p = \sum_{j=1}^{n} \left(\frac{p}{k}\right)_{gen_j} \omega_j^2 \, M \, \eta_j \qquad (8)$$

This is called the modal reconstruction method. Good reconstruction results are only achieved if all natural blade eigenmodes are considered, otherwise considerable errors in the reconstruction results are possible.

Identification of structural parameters, like the eigenmodes and eigenfrequencies, from testing techniques is always subject to measurement errors which may lead to an incomplete or faulty identification of higher order parameters. Accordingly the reconstruction results themselves will be faulty.

Reconstruction with the Williams method

Implementation of a method first suggested by Williams[8][9], results in a better convergence of the reconstruction method. This method is also called "mode acceleration method" by Craig[17].

According to Williams, quasistatic structural response dominates if the applied force $p_{(t)}$ changes very slowly in time, meaning quasistatically. If this is not the case, then inertial and damping forces must be taken into account. Williams used this fact in computing the structural responses of an airplane subjected to gusts and landing loads. Keeping Williams idea in mind, a partial substitution of y in eq.(1) leads to

$$M\Phi\ddot{h}_{(t)} + C\Phi\dot{h}_{(t)} + Ky_{(t)} = p_{(t)} \qquad (9)$$

The first two left terms in eq.(9) describe purely dynamical forces whereas **Ky** the quasistatic force is. Writing eq.(5) in matrix form, multiplying from the left with $\mathbf{m}\,\Phi\,\omega^2$, and performing some tedious matrix operations leads to

$$\boldsymbol{M}\,\boldsymbol{\Phi}\,\ddot{\boldsymbol{h}} + \boldsymbol{C}\,\boldsymbol{\Phi}\,\dot{\boldsymbol{h}} = \boldsymbol{M}\,\boldsymbol{\Phi}\,\omega^2\left(\boldsymbol{K}_{gen}^{-1}\boldsymbol{p}_{gen} - \boldsymbol{h}\right) = \sum_{j=1}^{k}\left(\left(\frac{p}{k}\right)_{gen_j} - h_j\right)\boldsymbol{M}\,\boldsymbol{\eta}_j\,\omega_j^2 \qquad (10)$$

Substitution of eq.(10) in eq.(9) gives the ***reconstruction equation*** with the implemented Williams method.

$$\sum_{j=1}^{k}\left(\left(\frac{p}{k}\right)_{gen_j} - h_j\right)\boldsymbol{M}\,\boldsymbol{\eta}_j\,\omega_j^2 + \boldsymbol{K}\boldsymbol{y} = \boldsymbol{p} \qquad (11)$$

The primary advantage of a reconstruction with eq.(11) to a purely modal reconstruction, lies in the fact that now only the significantly excited eigenmodes are required for the computations. These are usually lower order eigenmodes more easily identified.

Reconstruction method for rotating rotor blades

The structural parameters required for eq.(11) must, of course, be those of the rotating rotor blade. Measurement of these parameters on the rotating blade is very difficult if not impossible. Structural parameters for the non rotating rotor blade, on the other hand, are quite easily measurable.

A rotating helicopter rotor blade is subject to heavy centrifugal loading resulting in a "stiffening" of the blade structure. This centrifugal stiffening is responsible for higher natural eigenfrequencies compared to those of the stationary blade. With a specially developed numerical stiffening scheme, the measured stationary elasticity matrix E_0, and thus automatically also the stiffnes matrix K_0, is stiffened according to the actual rotor frequency. The resulting stiffened elasticity matrix E_Ω is used to compute the rotating blade eigenmodes and eigenfrequencies with an eigenvalue solver.

Hinged rotor blades can and must be considered in the numerical stiffening method, described extensivly in [7] and [16]. The first rotating blade eigenmode is a pseudo-rigid body mode. Due to the eccentric hinge location, the first eigenmode is not a straight but a curved line. With hinged blades, the blade flap angle time history must be measured as well. The overall blade deflection relative to the rotor plane is computed from a linear superposition of the elastic blade deformation and the measured flap angle. This overall blade deflection is the input quantity for determining the generalized coordinates from eq.(2) or eq.(7).

Rotor blade structural parameters

The most important parameters in the RM are the elasticity matrices for the main blade degrees of freedom. An elasticity matrix can be computed from theoretical blade stiffness data, but a measured matrix yields the best reconstruction results. Peculiarities or large changes in the blade stiffness distribution are automatically enclosed in a measured matrix. This ensures a physically correct representation of the dynamical blade properties. This is essential, since the measured, and later numerically stiffened, matrix is primary input for the computation of rotating blade eigenmodes.

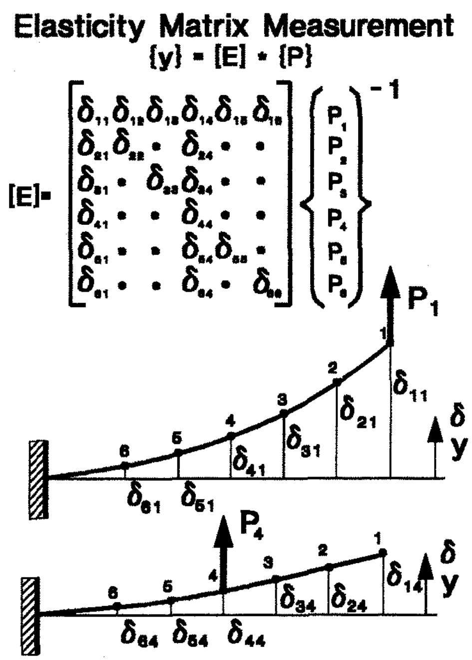


Fig.2 Rotor blade elasticity matrix measurement method and evaluation equation

A rotor blade elasticity matrix, whose inversion yields the stiffness matrix, is obtained from measuring the blade deflections resulting from applied forces at the lumped mass locations. Optical measurement techniques yield the best results, as the blade is allowed to bend without any constrictions originating from measurement gauges. The elasticity matrices for the model rotor blades in the wind tunnel tests were all measured optically with a maximum resolution of 1/100mm. Helicopter rotor blade elasticity matrices were measured with non fixed linear potentiometers. In Fig.2 the elasticity matrix measurement scheme is described.

An excellent method for checking the measurement accuracy is to compare measured blade eigenfrequencies and eigenforms with those computed from the measured elasticity matrix. If they differ very much, then smoothing and correction of the matrix or even a new matrix measurement must be performed. This can be performed in several ways as described in [16]. If, lets say the first five measured and computed eigenmodes correlate well, then the matrix may be used effectivly in RM evaluations.

The required rotating blade eigenmodes and frequencies in the RM computations are calculated numerically from the stiffened elasticity matrices by solving the special eigenvalue problem

$$\left(\boldsymbol{K}_\Omega^{-1}\boldsymbol{M} - \frac{1}{\omega^2}\boldsymbol{I}\right)\boldsymbol{y} = \left(\boldsymbol{E}_\Omega\boldsymbol{M} - \frac{1}{\omega^2}\boldsymbol{I}\right)\boldsymbol{y} = \boldsymbol{0} \qquad (12)$$

Modelling the rotor blade as a one dimensional, lumped mass system requires an optimal distribution of the physical blade mass at the lumped mass locations. This is not done in a way so as to equalize the total blade weight, but to achieve dynamic resemblance between modeled and actual blade. If computed eigenfrequencies do not correlate with measured, then possibly a correction of the lumped mass quantities could lead to better results. An equidistant allocation of lumped masses is optimal but not always practicable, e.g. because of the vicinity to eigenmode nodes, gauge locations or a desired higher resolution of reconstructed forces at a specific geometric location.

Blade response measurement

Measured rotor blade responses for evaluation with the RM may consist of local bending or torsional moments, local blade deformations or deflections, local blade accelerations or a combination of these. Bending and torsional moments are best measured with strain gauges applied at appropiate blade locations. Measurement of blade displacements or deformations is not so easy. Usually some kind of complex optical measurement technique along the rotating blade is required. Application and adjustment of the optical equipment on the rotor hub and rotating blade could be quite difficult. Furthermore, a measurement reference point or plane must be found and defined. Local blade accelerations are best measured with miniature accelerometers applied at the measuring stations, preferably in blade tip vicinity, where the accelerations would be large. Yet, as stated in [11] and also from our experience, accelerometers are not so suitable for blade response measurements. Due to the vibrationally induced change of the measurement axis relativ to the rotor plane, large undesired centrifugal acceleration components contaminate the desired blade vibratory information.

Our best rotating blade response measurements were aquired with strain gauge measuring units each consisting of two or four strain gauges. Gaukroger, Payen, Walker and Hassal used strain gauges in their rotating blade measurements very succesfully [10][11][12]. Blade response data measurements in our wind tunnel and flight tests were aquired solely from strain gauges. Special care must be taken in the gauge positioning. If applied in vicinity of rotating blade eigenmode nodes, only small signals in the magnitude of signal noise could result. Bending moments are best measured with gauges applied along the elastic blade axis. Torsional gauge signals should not be disturbed by bending information and vice versa. The best gauge application location is, if possible, on the main blade spar. Temperature influence is another important factor to consider, not so much in wind tunnel testing as in helicopter flight testing. Gauges located on the upper rotor side are heated up in sunshine, causing a zero drift of the gauge unit if not compensated in some way.

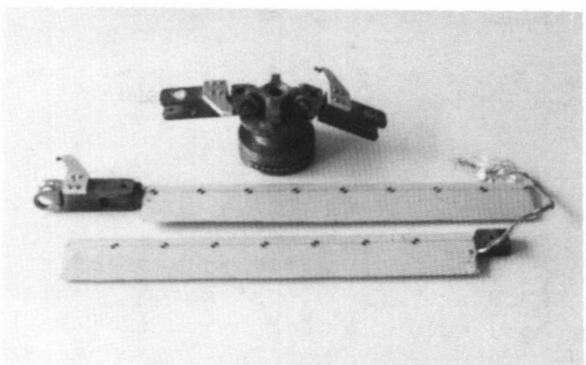
Strain gauge units are best calibrated with the stationary blade clamped cantilever type ensuring application of definite bending or torsional moments. The gauge signals resulting from applied moments define thus calibration factors for each gauge unit. Although the measured moments are obtained with calibration factors valid only for the stationary blade, the elastic deformation of the rotating blade (required for eq.(2)) can be computed with the stationary elasticity matrix E_0 and the measured "stationary" moments M_0 from eq.(13).

$$y = E_0 p_0 = E_0 \Delta X \hat{M}_0 = E_\Omega \Delta X \hat{M}_\Omega \tag{13}$$

ΔX is a geometric lever matrix, defining the local bending moments at the gauge locations resulting from the local air forces acting at the modelled mass locations.

Wind tunnel tests

In the göttinger type wind tunnel at the Institut für Luft- und Raumfahrt in Aachen, extensive rotor blade response measurements were performed during the last years. The model rotor blades had a profiled length of 0.41m and the rotor diameter was 1.1m. A NACA 0012 profile was used with a chord of 0.055m giving an aspect ratio of 7.5. The blade spar consisted of a 15x2mm strip of flexible springsteel centered at 1/4 chord. The blade itself was modelled from balsa wood covered with self adhesive tape.



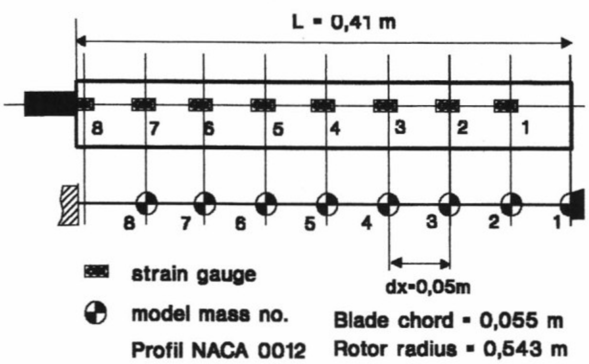


Fig.3 Steel model rotor hub and instrumented model rotor blades

Instrumentation consisted of strain gauges applied at 8 locations on both sides of the spar. The blades were attached to a fully articulated steel rotor hub mounted on the wind tunnel rotor test facility. Model blades and rotor hub are shown in Fig.3. The rotor test facility with mounted blades is depicted in Fig.4.

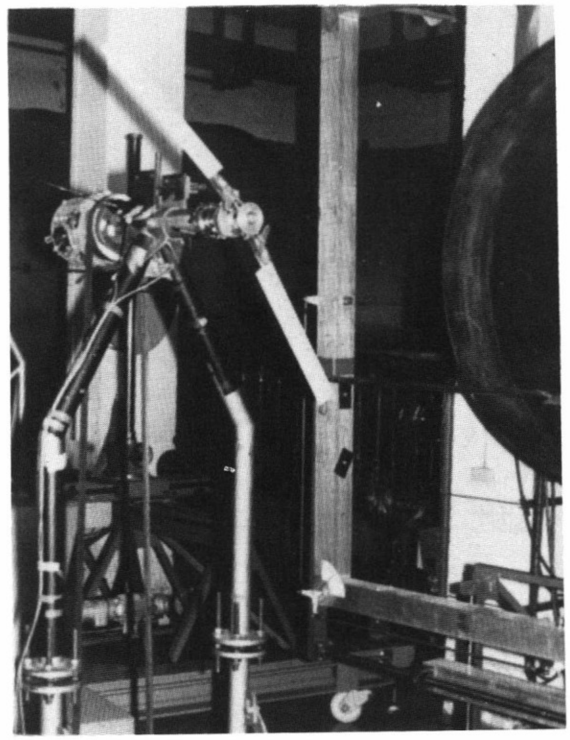


Fig.4 Rotor test facility with mounted rotor blades

There are several methods of transmitting electric test data from rotating to non rotating systems. The simplest is the mechanical slip ring method. Other similar systems use mercury as conducting medium between rotating and non rotating systems. Very elegant and versatile methods are those using infra red, ultrasonic or radio transmission. Our data aquisition system uses a battery powered radio telemetric system capable of transmitting simultaneously 12 different data signals. The miniaturized system is contained in 6 small modules together weighing about 0.7kg. The telemetric system is mounted in a special holder attached to the belt driven end of the rotor shaft (Fig.4). The transmitted test data is stored analogously on video tape by a special data recorder. The test data from the tape is finally digitized with a transient recorder and transferred to a personal computer for evaluation with the RM. The data aquisition system is presented in Fig.5

Eight strain gauge, a flap angle, a rotor azimuth and two accelerometer signals were transmitted simultaneously. The flapping angle was measured with a

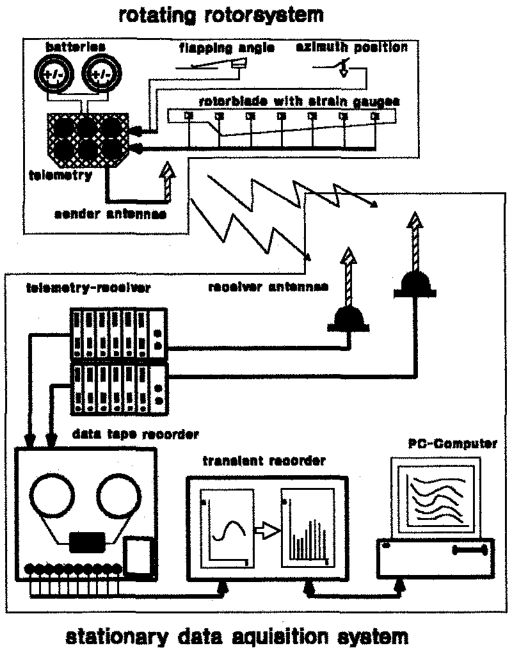


Fig.5 Data aquisition system for the wind tunnel and flight testing

strain gauges applied to a thin strip of steel attached to the flap hinge. Due to the periodical strip deflection during each rotor revolution, a signal proportional to the flapping angle was produced[16]. This measurement device method allowed a flap angle measurement with a mean resolution of ±0.25°.The exact rotor blade position during rotation was determined from a periodic signal generated by an inductive sensor mounted near the rotating rotor shaft. This signal is also used to determine the exact rotor frequency.

Response measurements were conducted with hinged and non hinged rotor blade. Typical helicopter flight attitudes such as hovering, forward flight and vertical ascent were simulated. Wind tunnel air flow was parallel to the rotor plane with no cyclic change in the blade angle of attack. Rotor frequencies were 500, 750 and 1000 RPM with resulting advance ratios of 0.05 to 0.35.

A typical reconstruction result of a simulated hovering flight is presented next. The rotor frequency is 1000 RPM with a 10° constant blade angle of attack. The blade is hinged. Fig.6a shows a qualitative representation of the reconstructed air forces on the model blade during one rotor revolution. Fig.6b shows the quantitative results. The air load distribution is as expected for a hovering flight.

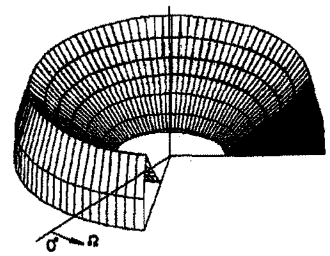


Fig.6a

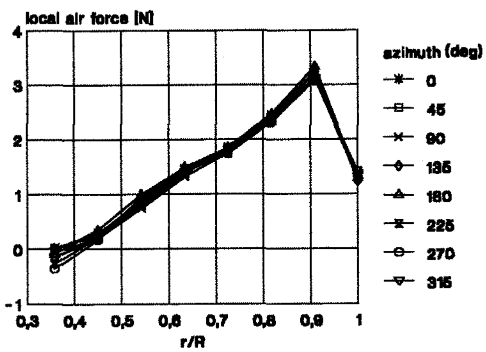


Fig.6b Reconstructed air forces for model blade in hovering flight. Hinged blade, 1000RPM.

In Fig.6b a non-zero force is present at the blade tip. This is physically not correct. As the computations in the RM are performed with a lumped mass model of the blade, the reconstructed forces are accordingly singular forces situated at the mass locations. The lumped mass model has a tip mass (see Fig.3) and thus the non zero tip air force. The reconstructed singular forces are equivalent to the continuous air load on the blade. In table 2, measured, theoretical and reconstructed model rotor lift are compared to each other.

rotor frequency RPM	theoretical rotor lift Ca'=5.7	measured rotor lift [N]	recon. rotor lift [N]
500	2.8	3.1	3.2
750	6.3	6.7	7.2
1000	11.2	11.7	12.3

Table 2

Flight tests

Flight tests with Kamov-26 and MD Hughes 500 helicopters were performed in Hungary during the autumns of 1989, 1990, 1991 and 1993. In this paper only a very small part of the results from flight testing can be presented. Detailled presentations have been published in several publications [5][6][7][16] to which the author kindly refers the reader.

The MD Hughes 500 helicopter has a five bladed main rotor, a conventional tail rotor assembly and is powered by an Allison turbine. Its rotor blade is built from aluminium with a central c-spar and weighs about 12kg. It has a NACA 0015 profile and a constant chord of 0.185m. The blade has a profiled length of about 3.5m and the rotor diameter is 8.1m. The photograph in Fig.7 shows the test helicopter just after take-off.

Fig.7 Test helicopter MD Hughes 500 with telemetric system mounted on top of the rotor hub.

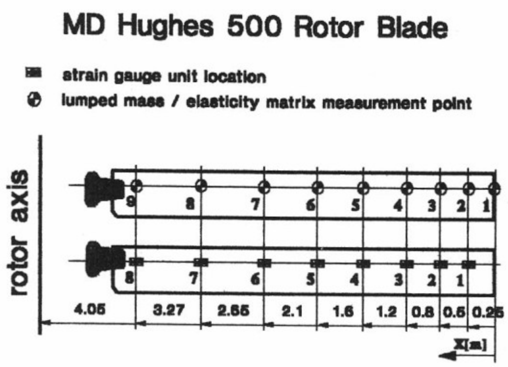


Fig.8 MD Hughes 500 rotor blade with strain gauge locations

The MD Hughes 500 rotor blade with the locations of the strain gauge measurement points and the lumped mass locations is shown in Fig.8. The gauge positioning is not equidistant, affording thus a dynamically optimized lumped mass modelling.

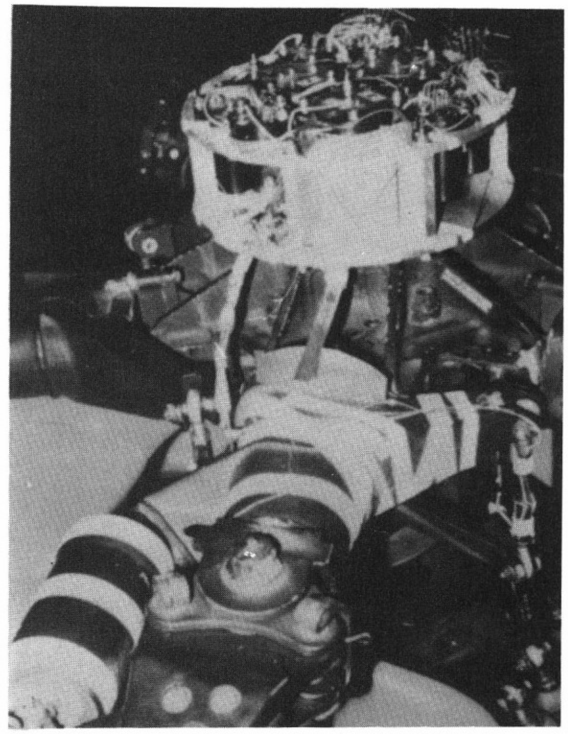


Fig.9 Telemetric system mounted on top of the MD Hughes 500 rotor hub

As the rotor blade structure was not to be damaged or altered, the strain gauges were applied directly to the blade surface. The gauge wiring, consisting of 0.25mm diameter insulated copperwire, was attached to the lower back side of the blade and covered with very thin self adhesive tape. The flap angle measurement device was similar to the one used during the wind tunnel tests. A thin steel strip with applied strain gauges was proportionally deformed according to the flap angle at the blade hinge. Azimuth blade position could be determined according to the signal given by a periodically occluded light sensitive diode system. Figure 9 shows the telemetric system set in its special aluminium holder mounted on top of the rotor hub. In the center of the foto, the flap angle measurement device is visible.

Hovering flight reconstruction results correlate very well with theoretically computed air load distributions [16]. The reconstructed rotor lifts are the same as the pre flight measured helicopter weight. In Fig.10a+b reconstruction results for the Hughes helicopter flying at 100 knots are shown. A qualitative representation of the singular "local" air forces is given in Fig.10a. The local forces are connected by lines to

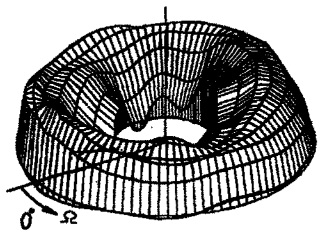


Fig.10a

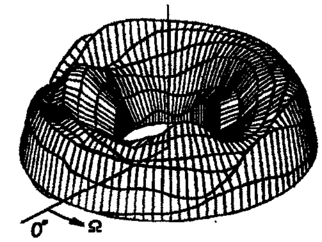


Fig.11a

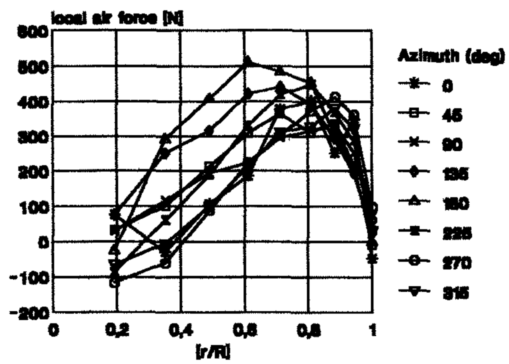


Fig.10b Reconstructed air forces for the Hughes 500 at 100 knots

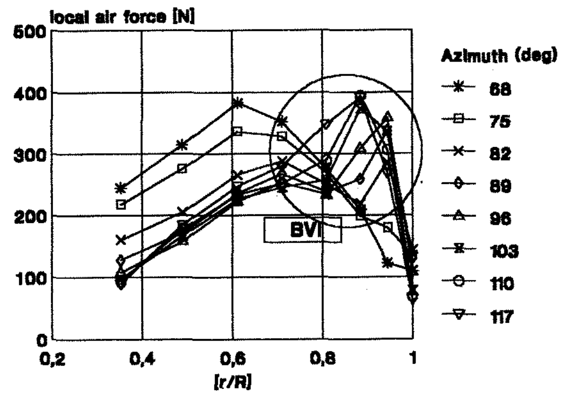


Fig.11b Reconstructed air forces for the Hughes 500 at 20 knots

give an impression of the blade load distribution. The diagram in Fig.10b shows the force distribution at eight different rotor azimuth positions. Two distinct effects are notable. In the vicinity of 0° azimuth a strong disturbance of the air force in blade tip vicinity is present. A possible explanation for this could be an interference between the tail boom, the tail rotor and the main rotor system. The second notable effect is located at about 270° azimuth. Due to the high forward flight speed, a region of reversed air flow at the inner blade region is present. The reconstructed air forces show a negative tendency which could be expected on behalve of the reversed air flow.

Very interesting reconstruction results are those for a flight speed of 20 knots shown in Fig.11a+b. The qualitative representation (Fig.11a) is quite different to the one for the 100 knots flight speed case. Eye catching are two disturbances at about 80° and 280° rotor azimuth. They belong to blade vortex interactions (bvi). The bvi at 80° is shown quantitativly in the diagramm of Fig.11b.

In Fig.12 the reconstructed force at mass no.2 (r/R=0.94) for one rotor revolution is shown. The first interaction at about 80° begins with an air force decrease followed bei an increase. According to the rotational orientation of the disturbing vortices this is to be expected. The contrary holds for the 280° interaction. Here first an increase followed by a decrease of the force time history is seen. This also corresponds to the vortice rotational direction. Actually, the shown interactions are not resulting from a single tip vortice interacting with the blade, but from many tip vortices converging at the interaction points. In forward flight the five bladed rotor disc is uniformly underlaid with circular tip vortice paths wandering to the rear of the disc. At the left and right side of the rotor disc the vortice paths lie very close to each other, viewed from the top of the disc, and the induced wind velocities are thus stronger than elsewhere on the rotor disc. Because of this, the bvi are extremely strong at the left and right disc sides.

In his survey of airloading on rotor blades published in 1983, Hooper[19] evaluated pressure measurements conducted on

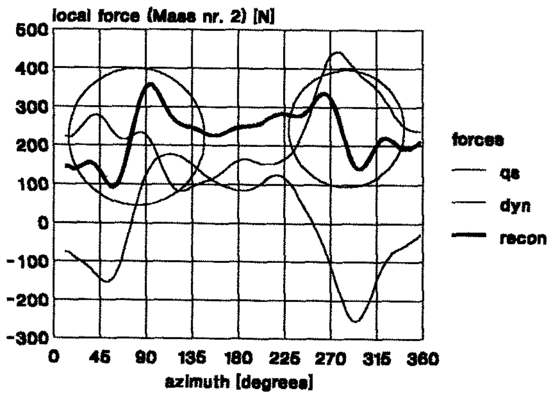


Fig.12 Reconstructed local force at Mass no.2 (r/R=0.94)

helicopter blades in the U.S.A..

In Fig.13 two of Hoopers evaluations are compared to the reconstructed air loads of the MD Hughes 500 rotor blade at a flight speed of 20 knots (advance ratio = 0.05). The reconstructed local forces have been transformed to air loads so as to allow a direct comparison. In Fig.13a, the air load on a Bell UH-1 rotor blade is shown. This is a two bladed helicopter. Rotor blade air loads for a five bladed NH-3A helicopter are shown in Fig.13b. These air loads are more directly comparable to those of the reconstructed MD Hughes 500 in Fig.13c. In all three diagramms distinct bvi can be seen. The time histories of all three bvi resemble strongly to each other. This is an indication that the reconstruction method can resolve high frequent aerodynamical blade effects very well and at the correct locations.

Concluding remarks

A method for determining the rotor blade air loads from in flight measured structural blade responses, has been presented in this paper. Only a short review of the basic equations was possible in this paper. Nevertheless the principal idea behind the reconstruction method ans the basic equations have been described. The reconstruction method has been tested and verified very thoroughly, and evaluations of measured rotor blade response data yielded good to excellent blade air loading results.

Results of model rotor blade wind tunnel test data evaluations proved, that the RM is capable of determining high frequent aerodynamical effects accurately. The reconstructed air load distributions compared very well with theoretically computed distributions. A maximum mean error of about 5% between measured and reconstructed rotor lift for the simulated hover tests proves the efficiency of the reconstruction method.

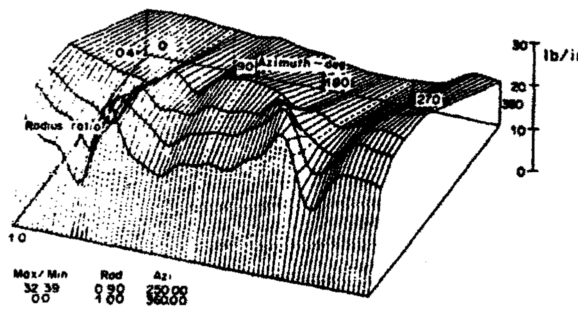


Fig.13a Rotor blade air load of a Bell UH-1 at an advance ratio of 0.072 (Hooper [19])

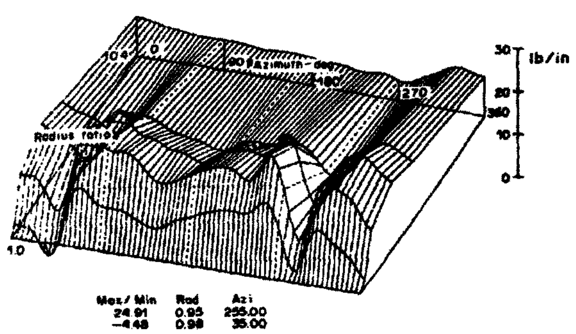


Fig.13b Rotor blade air load of a NH-3A at an advance ratio of 0.066 (Hooper [19])

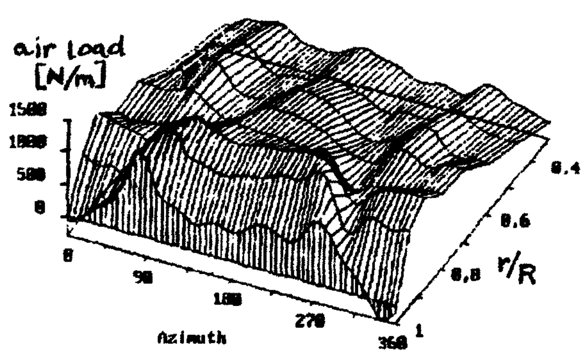


Fig.13c Reconstructed rotor blade air load of a MD Hughes 500 at an advance ratio of 0.05 (Lindert [16])

Reconstruction of rotor blade air loads from response data measured during flight tests with instrumented helicopter blades yielded also very good results, comparable to published pressure measurement results. Preparation and instrumentation of the rotor blades with commercial strain gauges was simple and inexpensive. The telemetric system is very much suited for data transmission in helicopter flight testing. Reconstructed blade vortex interactions of the MD Hughes 500 blade at low flight speeds agree well with bvi found in published evaluations of blade pressure measurements conducted on a NH-3A five bladed helicopter.

Although the here described reconstruction method has been developed and applied here on rotating rotor blades, there is actually no restriction to its applicability. The measured responses of any technical structure, for example like airplane wings, rocket structures or chimneys, can be evaluated with the reconstruction method, as long as the structural and dynamic parameters are known. The reconstruction method is, compared to most pressure measurement techniques, an easy to use and relative inexpensive method. In some cases, such as the determination of spanwise wing loading, the RM could even be a feasible alternative to pressure measurements requiring extensiv and complex preparations and blade instrumentation.

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