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in subject of

AERODYNAMIC AND DYNAMIC INVESTIGATION OF ROTOR BLADE LOADS

he compete with for apply of Ph. D. degree

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Introduction

My foregoing activity has closely engaged to the helicopter rotors. This has caused by my first flight was with a Ka-26 type helicopter too. Afterwards during my practical experience I could not get enough accurate information about the rotor blades neither from the crews nor from the technical documentations. By this reason I have decided myself that I had to get the missing information. The first bigger step was my MSC diploma piece what was followed by any other publication and finally this dissertation in the subject. By this essay I have analysed the steady linear flights of Ka-26 helicopter. The main cause on type choosing was that great experimental measurement at first in Hungary aimed for determination the rotor blade air loads really in flight with this type [1] and I have already in some respects processed the results in some of my foregoing works.

I. The aim of process

My aim was to make a technical-mathematical model for write the aerodynamic-dynamic-aero elastic behaviour of coaxial rotor system in a steady linear flight. For reaching the goal I had to analyse the rigid and elastic blade motions, the flow area above the rotors and the aerodynamic forces acting on blades with taking into consideration the effect of top rotor and unsteady effects of variable flow too.

The base of calculation is the combined blade-element momentum theory with the ONERA model [2] for unsteady flow effects, with the effect of top blade tip vortex and the effect of control system too. By this way the induced velocity field and the unsteady effects can be calculated. In case of success, these results can be used by the calculation of helicopter performance, equilibrium states, and finally but not at least for the investigation of rotor blade's life time with the calculation of the loads. The combined blade element momentum theory in English abbreviation BEMT or CBEMT, is a well known theoretical method. The zero resulted effects of blade tip vortices can be taken into consideration with using of the vortex theory complement added by me, that missed from the original theory.

II. Overview of the literature

By any investigation of the air loads of rotor blades we have to consider even the absolute volume or the spatial (here along the blade) and temporal (here azimuthally) distribution of them. The eligible practical methods are the different structural measurements, what could be real [1] [3] and model experiments [4][5] too and try to calculate the loads on the base of structural reaction. The following practical group is the group of aerodynamic measurements what determine the air loads along the rotor blades with measurement and continuous record of static pressure mainly in a wind tunnel. These methods have in practice great difficulties and the measuring equipments reacts on the strength or the aerodynamic properties of the blade. Adversely the big research institutes used them with success before th computer based simulations [6]. Newly the flow field around the rotor can be determined with much more sensitively equipments (heated anemometers, laser, and Planar Doppler Velocimetry (PDV) method, that is an optical method able to measure the velocity field in 3D) even 1:1 rated wind tunnel [5] because of the full accomplishing of the similarity requirements is almost impossible. One of the oldest method is the momentum theory was used successfully by planes but in case of rotorcrafts it can be used only with further improving. These improving are the application of those auxiliary functions that approximate the induced velocities of ideal rotor to the real one, consider with the place and advance ratio. Such function is the Glauert's [7] triangle velocity distribution giving a good approximation. Just this method can't contact the results with the cover ratio, the geometry and aerodynamic characteristic (and it's change), and the effects of the tip of blade (compressibility, vortices), the equilibrium state and the advance ratio of rotorcraft [8]. Nowadays the momentum theory come to the front with the spreading of training devices and increasing of the reality requirements due to it's fast computation [9].

The next more accurate method is the Mangler and Squire method (pressure-potential theory) that is a practical application of the velocity and acceleration potential theory, beginning with Euler equation. The base thesis of method is the pressure distribution is the Ψ potential function as a solution of Laplace equation. The $\Psi(x,y,z,t)$ is equal with the amount of $-(p-p_0)/\rho$, that would be mostly important by consideration with the compressibility and this amount is named as acceleration potential – it is a function of the space coordinates ant the time too –and those mathematical model based on this conception can be made with using of pressure dipoles running in the time with a q(t) time function. In case of small velocities this method is very accurate but by bigger velocities mostly in the wake becoming unreliable so by the examination of the effects of the fuselage, tail booms, stabilisers and tail rotors is not usable, furthermore it gives not any contact between the rotor geometry, the structural properties, the control and the aerodynamic operation. [10] [11].

The Pitt-Peters method is a developed process of the previous one and it is very popular by the examination of advance flight operation because of it uses uniform induced velocity distribution, consider with the torsion of stream tube due to advance movement [12]. This model has brought an important development in the examination of longitudinal change of wake in case of advance flight, nevertheless this method also do not consider the rotor geometry, and do not contact with the aerodynamic, structure, control properties and the real flow (compressibility, blade interactions), so it's accuracy is limited [13].

The combination of blade-element and momentum theory give any possibility the using of 2D profile characteristic and consider with the geometry and (chord distribution, geometric and aerodynamic twist) and next to this consider with the effects of operational parameters, because of it's base philosophy is the examination of aerodynamic phenomenon in the narrow pieces of the blade. Contemporaneously by starting of process we have to use an uniform induced velocity distribution too, by this reason the results – induced velocities, thrust, moments - would not join with the real equilibrium state. We would be more successful in that case the equilibrium state of rotor blades could be examined with the examination of the whole helicopter equilibrium and with taking into consideration the movements of rotor blade by the profile characteristics determination. So we can reach the equilibrium state – after giving an initial induced velocity distribution – for example with approximation during every rotation. The flow field gained by this reason is much more realistic as those idealized picture that is clearly based on momentum theory. This method is important for the constructors by the way of determination the initial general constructional directives and finally it gives contact between the flow and the geometric-aerodynamic properties of rotor blade [6].

The vortex theory is the most universal method to determine the time average and momentary velocity fields in the infinite space by lifting and thrusting propellers with the application of physical-mathematical modelling of vortex systems. This method is usable for investigation of the time –dependent flows, writes in detail the blade interactions better than previous ones, and help us by the examination of the loads in the zone of blade tips. The simplest models replace with the rotor blade with a constant circulation vortex filament in axis flow [14]. The next step was to take into consideration the effect of blade tip vortex as lift decreasing in the tip zone with using an unsteady circulation along the rotor blade [15]. From this one was developed the method of equivalent linear vortex system [16], so it's effect is equivalent to the superposition of the effects of bound vortex, tip and root vortices, trailing and shed vortices too. Consideration of the finite blade number was a quality leap by the way of development [17] [18] [19] [20] [21]. The constructors need to know the load distribution along the cord of rotor blade too. To solution this problem was developed the method of lifting surface-approach [16]. the next phase of development was the taking into account of the stream tube contractions. [21] [22]. Nowadays the 3D models are the most current for the detailed examination of advance flight [16] [22] [23]. Due to the spatial and temporal freedom in contact of aerodynamic phenomenon the vortex theory arrest the attention of the theorizers, and professions of aerodynamic, aero elastic and noise phenomenon so these activities result a continuous broaden of the literature [24] [25] [26]. Parallel of this vortex theory based computer programs are continuously developed with the aim of determination the rotor blade air loads, examination of the aero elastic phenomenon, the rotor-airframe interaction [27], the effect of free wake deformation [28] [29] in case of finite blade models, using by performance computation and by so special tasks as the noise examinations. Next to the respect of the method's performance that can be seen the results are often misleaders by this reason during a vortex theory based programme it is very important to built in different preservations against the possibilities due to mathematical singularities without any physical base. [8].

The local-momentum theory was developed by two Japanese scientists Azuma and Kawachi [30]. Their goal was to determine the time average and momentary induced velocity field with satisfactory accuracy next to much simplest computation process than the above mentioned vortex theory based ones. The method is the especial mixture of the blade element, momentum and vortex theory and it's base is a real wing and it's induced velocity modelling with placed above, decreasing side, elementary wings with elliptical circulation distribution. The experimental and computed results are fitted well and on this base it can be state this method is well usable and simple method so the time of process would be greatly short.

III. The means of research and the applied processes

My goal was to make a technical-mathematical model for write the aerodynamic-dynamic-aero elastic behaviour of coaxial rotor system in a steady linear flight, mainly in case of bottom rotor. In consideration of my strongly limited computational capacity and measuring possibility as well as the relatively simple programming ability and satisfactory accuracy, I have chosen the base of model the combined blade element momentum theory supplemented with effect of trailing vortices. Increasing the accuracy I have considered thee movements of rotor blade, the flow above the rotor, the aerodynamic forces on the blade, the effects of top rotor, the unsteady flow around the profiles, the elastic deformations and the effect of tip vortices. For the solution of problem I have developed the model of Tamás Gausz Ph.D. written in version 3.5 of Power-Basic [31] and based on the combined blade-element momentum theory for single rotor case. I have used the MATLAB too mainly for filtering of the results of measurements and Microsoft Excel for completions of those processes were not programmed, and for the graphics. In case of using the momentum theory the cross section of stream tube of the coaxial rotor system, what I have given as a function of the place along the rotor disc. By the way on a coordinated place knowing the distant flow velocity, the pressure and the density, the induced velocity could be simply determined by using of momentum theory. Using the blade-element theory in case of bottom rotor we have to consider even the classical components of the flow or the normal and tangential induced velocities of top rotor, the velocities are induced by the tip vortex of top rotor on the bottom rotor disc, the effect of tip vortex on the lift near the tips (the lift coefficient was decreased to zero with a polynomial by the tips) and the effect of unsteady flow on the profile characteristic with the ONERA model. By considering of the effects of top rotor those area is on the bottom rotor disturbed by the flow of top rotor had to be determined in the function of advance ratio. Here the setting back of the stream tube was considered. The flapping and feathering motions were considered with their simplified classical differential equation by this way consider with the control law and the effect of flapping compensation. In the computation the bending deformation was considered with the linear combination of the first four free vibration with their azimuthally coefficients, those azimuthally coefficients were very necessary for the calibration of the model and for the strength analysis too.

The computation process have two parts: In the first part the program calculate the induced velocity-distribution, thrust, horizontal and side forces of the top rotor. The steps:

1. The program reads the geometrical, structural and aerodynamic dates;
2. Computation the preliminary induced velocity distribution on the base of Glauert's approximation and calculation the thrust force of the whole helicopter with classical method;
3. Numerically integration of differential equations of flapping and bending motions, during one revolution. The calculation of the flapping motion and bending deflections has included the unsteady-compressible lift coefficient, and the equation of the connection between the flapping and feathering motion. This calculation uses polar coordinate system;
4. The force distribution over the rotor surface is known the corresponding (new) induced velocity distribution can be calculated in a Descartes coordinate system. On the base of these calculations – in order to investigate the equilibrium state of the helicopter – can be determined the horizontal, side and trust force of the rotor.
5. After these steps the program goes back to flapping calculation – while the rotor blade turns to the generalised equilibrium state. This can be realised practically after 10 revolutions. If the equilibrium state is not reached, then the P_0 ;P_1;P_2 parameters can be changed.
6. We have to store the values of the equilibrium state.

The second part is same as the first one, only by the 2^{nd} step we have take into consideration the foregoing computed and conformal positioned induced velocities of the top rotor and expand with the velocities induced by the top rotor tip vortices.

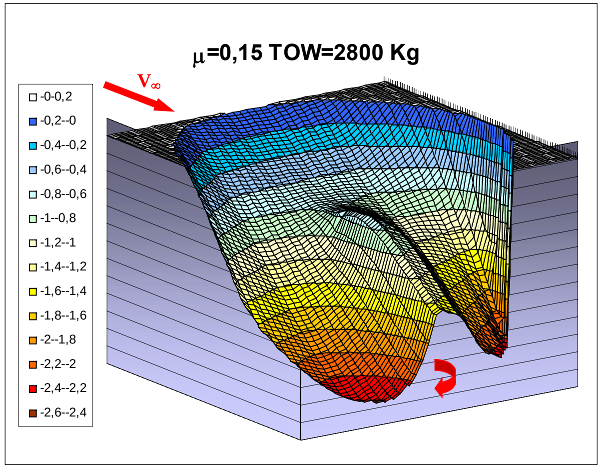
For the calibration of model I have used the results of a measurement already was published in the [1] and was analysed in my previously papers [3] [32] [33]. Without detailing the base of the measurement was the signs of tensiometric stamps calibrated for unit-moment values on a bottom rotor blade of a Ka-26, flapping angle transmitter and rotation per minute transmitter were transmitted to the earth with a telemetric system during steady level flight with different advance ratio. The differential equation of flexible chord can be easily solved numerically with the linear combination of the above mentioned azimuthally coefficients and free vibrations. So giving same operation parameters near the measured moment values could be calculated with the model, in a given azimuth and place along the rotor blade. For determination of the deviation between the measured and with a dipole Chebisev filtered and model computed moment values I have used a deviation function with the space of quadratic integral able functions, computed by

scalar product and well usable in case of any constant approximation [34]. The Table 1. shows the above mentioned deviations in case of μ=0,15 advance ratio.

Meas. places	No1	No2	No3	No4	No6	No7	No8
Deviation [%]	14,4	15,01	24,38	22,04	18,59	21,77	23,22

Table 1. Relative deviations of the two results on the measuring places

On the base of results above I have looked at the model as a valid one. The whole both the normal and tangential induced velocity field of the helicopter was calculated by different advance ratios as an aerodynamic application of model. One of these results (the normal induced velocity field of bottom rotor) is shown by the Picture 1.



Picture 1. The normal induced velocity field of bottom rotor [m/s]

The whole calculation of rotor blade's loads would be calculated with those movements were determined by the model so by this reason it would be possible the calculation of load on the base of static – with superposition of the external loads – and on the base of dynamic – calculation of the internal loads as to be in balance with external ones. By the calculation of static bending load the following effects had been considered the moments and forces from the lift, the moments and forces from the lift centrifugal force, the moments and forces from the mass forces.

The internal stresses from the elastic and rigid bending motion were considered as the base of dynamic bending load. The following equations coming - from differential equation of flexible chord - were used to calculate the dynamic bending load as a bending moment:

$$M_{DIN}(x_l,\psi) = IE(x_l)Y''(x_l,\psi) \qquad (1)$$

and from this moment the stress in the outermost cord of the bended structure – in this case the bottom outermost fibre of the spar of rotor blade – can be calculated with the following equation:

$$\sigma_{DEF} = \frac{\partial^2}{\partial x^2} \sum_{i=2}^{4} \Phi_i(x_1) H_i(\Psi) Ee(x_1) \quad (2)$$

The reduced stress values in the table 2. by both –dynamic and static too – cases were calculated with the following equation [35]:

$$\sigma_{red} = \sqrt{\sigma_r^2 + 4\tau_Y^2} \quad (3)$$

where in static case σ_r is a summary of follows: the bending moment from lift force, the bending moment from centrifugal force, the bending moment from mass force, tensile stress from centrifugal force. In case if shear only the lift was

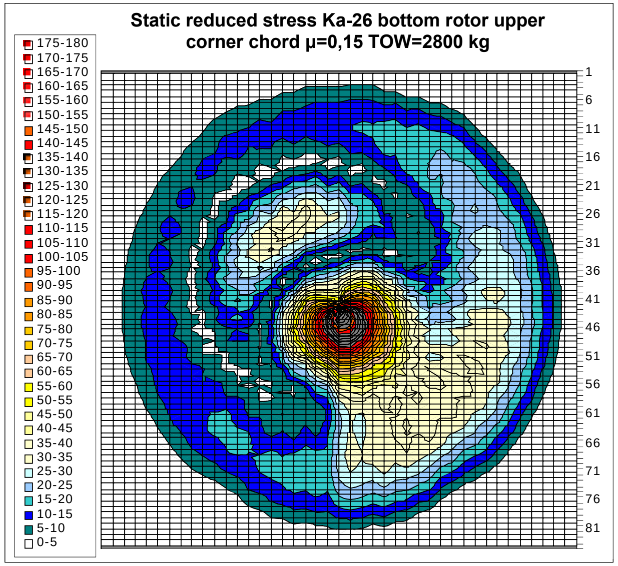
Adv. ratio	$\sigma_{din}/\sigma_{stat}$	$\sigma_{redStat}/\sigma_B$	σ_{redDin}/σ_B	ε_{Stat} (m/m)	ε_{Din} (m/m)	τ_Y/τ_B
μ=0,025	12/85 (14,1%)	135/420 (32,14%)	56/420 (13,33%)	0,0045	0,0019	2,8/40 (7%)
μ=0,15	15/180 (8,3%)	180/420 (42,85%)	60/420 (14,28%)	0,006	0,002	2,6/40 (6,5%)
μ=0,25	19/325 (5,8%)	330/420 (78,57%)	66/420 (15,71%)	0,011	0,0022	3,2/40 (8%)

Table 2. Relative stresses and elongations

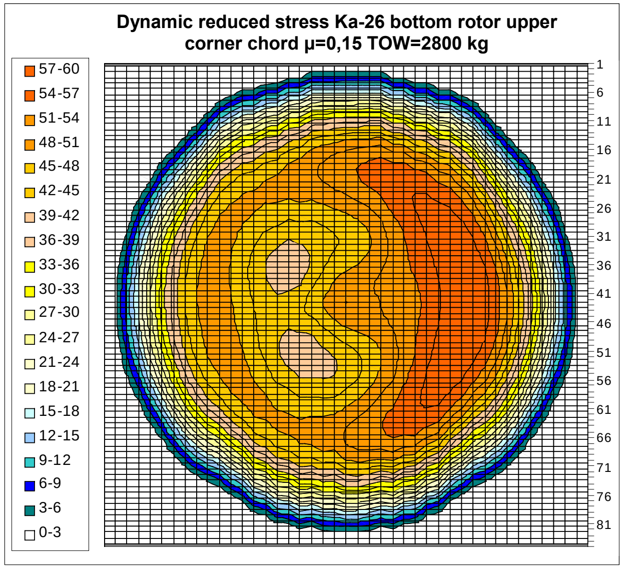
considered and related to the shear strength.

In dynamic case σ_r is a summary of follows: internal stresses from elastic deformations due to dynamic forces, tensile stress from centrifugal force as above. The table Table 2. shows the absolute and relative values of the stresses and elongations. The strength properties of rotor blade material were sourced from the literature [36].

The following pictures show the distributions of the static and dynamic reduced stresses along the rotor disc.



Picture 2. Distribution of static reduced stress [MPa]



Picture 3. Distribution of the dynamic reduced stress [MPa]

IV. Theses

During my work I have reached the following new results:

1. **I have developed a technical-mathematical model for examination of aerodynamic, dynamic and aero elastic behaviour of the helicopters having coaxial rotor, within**

   1.1. I have developed advance the **B**lade **E**lement **M**omentum **T**heory for simple rotor, so it would be able for

   1.1.1. Determination the cross sections of stream tube of a coaxial rotor system;
   1.1.2. Calculation of tangential velocity components;
   1.1.3. Using the steady wind tunnel measured profile characteristics in case of unsteady flow;
   1.1.4. In case of bottom rotor blades taking into consideration the normal and tangential velocity components of the top rotor;
   1.1.5. In case of bottom rotor blades taking into consideration the induced velocities of the top blade tip vortices on the bottom rotor disc;

   1.2. I have divided the flow above the bottom rotor into two zones: the first is the undisturbed (free of any effect of top rotor) and second one is the zone is disturbed by the effects of top rotor, and I have determined in the function of advance ratio how these zones are placed. This needs to know the angle of attack of rotor, setting back and contraction of top rotor's stream tube. The next equation shows the function angle of attack of rotor in case of carrier modification of Ka-26 type helicopter by TOW=2800kg:

$$\propto_R = -0{,}0034((V_\infty+20)/20)^3 - 0{,}1792((V_\infty+20)/20)^2 + 0{,}0223(B67+20)/20$$

   where V_∞ in km/h. The function of stream tube setting back in case of the above mentioned configuration an TOW could be written as follows:

$$X_{ST} = 0{,}0113((V_\infty+20)/20)^4 - 0{,}234((V_\infty+20)/20)^3 + 1{,}3829((V_\infty+20)/20)^2 - 1{,}2922(V_\infty+20)/20$$

   1.3. The set of differential equation for the movements of rotor blade was joined with the above mentioned CBEMT method {this is shown by computer program of the technical-mathematical model of bottom rotor examination} taking into consideration the follows:

   1.3.1. The flapping and feathering motions of the blade because of the conjugate flapping-feathering vibration is the central question of the operation of a helicopter rotor so for the correct analysis it have to be considered;

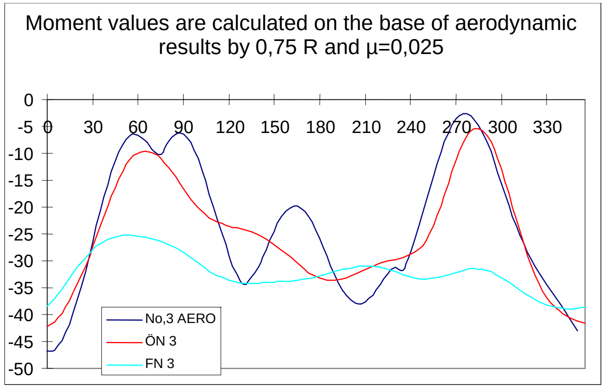
   1.3.2. The bending deformation of rotor blades what increase the accuracy of computation and strongly needed by the strength analysis;

2. **On the base of technical-mathematical model I have investigated the aerodynamic behaviour of the bottom rotor of Ka-26 coaxial rotorcraft, within this**

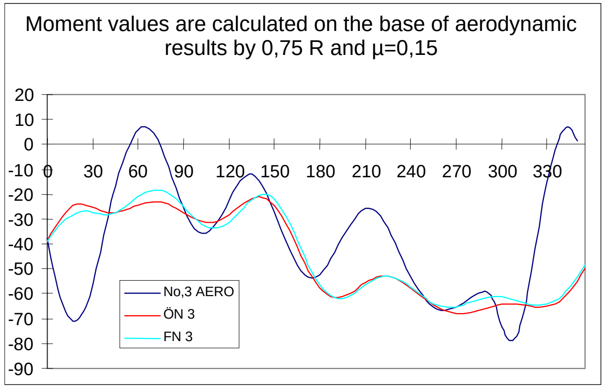
   2.1. I have established that the flow around the bottom rotor blades are not changed significantly due to the effect of induced velocity field of top rotor;

   2.2. The diameter and place of the stream tube of top rotor is changed in the function of advance ratio and there is always an area to be not disturbed by the flow of top rotor;

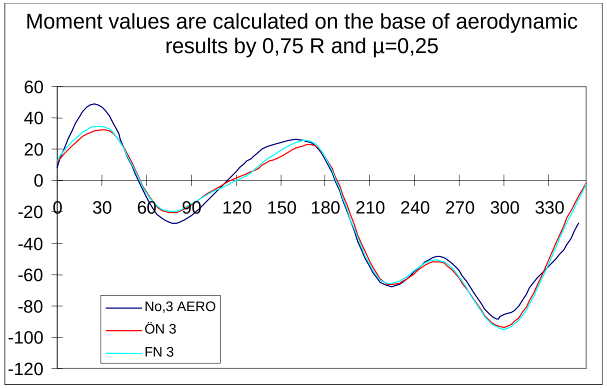
   2.3. The top blade's tip vortices act on the load of bottom blades only in case of medium advanced operation and the effect of the induced velocities is the higher in case of small advance the or hanging. On the other hand in case of high speed operation the effects of top rotor on the loads of bottom one is insignificant. This is showed by the 4.-6. pictures what shows the effects of top rotor in the relative radius of 0,75 (is place is the place of No. 3 of the measure rotor blade) The symbols in the pictures are the follows:
   – No. 3 AERO: Results are calculated with the model considered with the most effects;
   – ÖN: Results are calculated with the model without the effect of top blade tip vortices;
   – FN: Results are calculated with the model without any effects of the top rotor.



Picture 4. The effects of top rotor on the bending moment of bottom blades by small advance



Picture 5. The effects of top rotor on the bending moment of bottom blades by medium advance



Picture 6. The effects of top rotor on the bending moment of bottom blades by high advance

3. **I have developed a model connecting to the model stated in thesis 1 for determination the really (dynamic) loads of the rotor blade and I have applied this strength model the foregoing examined bottom rotor blade of Ka-26 helicopter, within this:**

3.1. I have determined the particular static (in this case calculated bending moment on the base of external loads) and dynamic in this case calculated bending moment on the base of bending deformations – ergo the really acting) loads and I have determined the reduced stresses on the base of them and compared these stresses to the breaking-load (Table Table 2.).

3.2. I have determined the really deformations of the bottom rotor blade and calculated the maximal reduced stress of them – this is the dynamic stress, respectively I have called it as dynamic stress. It can be well seen on the base of values of the table Table **2.** that values calculated on the base of external loads and called for static are much more higher than those values are calculated on the base of deformations as internal stress and really existing. This goes to show in real operation situation due to the fast change of loads the structure has no enough time to carry those loads were calculated on base of static point of view. This statement proposes the follows:

3.2.1. The rotor blades are constructed on the base of static aspect (forasmuch as the rotor blade of Ka-26 rotorcraft was constructed at 1959 and then were not so computational background as were able to determine the dynamic loads) are exaggerated structures.

3.2.2. Using dynamic loads new construction limits could be determined as a more economic solution or the life time of these structures could be lengthen on this base.

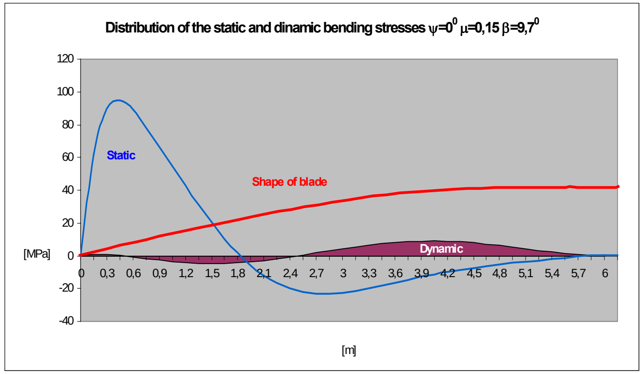
3.2.3. It is ascertainable that the relative elongation of rotor blades of Ka-26 helicopter exceeds nowhere the 0,004 value [37] [38] [39] [40] so by this way the life time of blade goes to the infinite when the mechanic loads are considered only. On this base (considered with practical experiences in the subject [41]) the life time of the blades would be not infinite due to the environmental effects, but it is expectable this life time will be very high. This is confirmed by the present life time what is 4000 hours or 16 years – almost two times higher than the original one was. Surely there would be further life time limit extend in the future based on the theory of small deformation due to dynamic loads.

3.3. On the base of pictures 7. and 8. I have determined the static and dynamic critical sections of the rotor blades what are the follows:

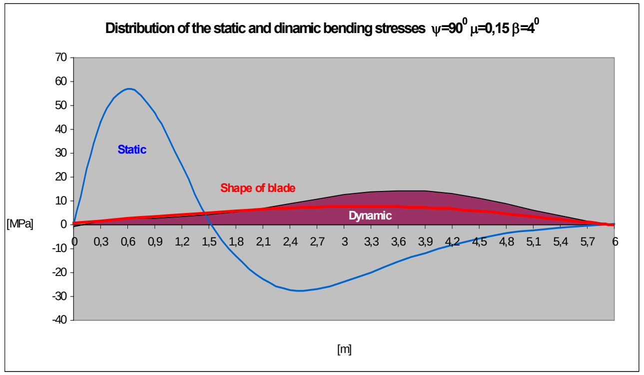
3.3.1. Critical segments on the base of static bending load are the segments 0,3-0,6 m and a 2,1-2,7 m distance from the root;

3.3.2. Critical segments on the base of dynamic bending load are the segments 1,5-1,8 m and 3,9-4,4 m distance from the root – this is confirmed by the [42], where exactly segments were called as critical ones.

3.3.3. Both static or dynamic based reduced stresses show that the root of rotor blade is the most critical segment due to the great effect of centrifugal load.



Picture 7. Azimuthally intercept of shape of blade and strength distributions



Picture 8. Azimuthally intercept of shape of blade and strength distributions

V. Literature activity

My publications in the themes of theses:

Abroad published journal article in foreign language:

1. D. Szilágyi**,** „Rotorcraft Aviation Today in Hungary” *Transactions of The Institute of Aviation Scientific Quarterly 1-2/2002 (168-169)* pp. 23-24. Institute of Aviation, Warsaw 2002.

Foreign language performance published in international conference proceedings:

2. D. Szilágyi, “*Rotor blade air loads determination on the base of structural deformation*” II. Avionics Conference Poland, Jawor 1998. 09. 09-12. Bieszczady ’98 Poland 1998.
3. D. Szilágyi, „*Aerodynamic Investigation of the Coaxial Rotor System*” Proceedings of the 7th Mini Conference on Vehicle System Dynamics, Identification and Anomalies pp. 473-480 Faculty of Transportation Engineering, Budapest University of Technology and Economics, Budapest 2001.
4. D. Szilágyi, *“Aerodynamic Investigation of Coaxial Rotor System”* Mechanica Awionika NR 186 Tom 1 pp. 261-269. Rzeszow (Poland) 2001.

Journal article in Hungarian language:

5. Szilágyi D, „*Koaxiális Rotorok Aerodinamikai Vizsgálata*”. GÉP folyóirat 2001/8 sz. pp 19-23 GTE Budapest, 2001.

Conference proceedings in Hungarian language:

6. Szilágyi D, *„Rotorlapát légerőterhelésének meghatározása a szerkezeti deformációk alapján*” XIV. Magyar Repüléstudományi Napok Szolnok, ZMNE RTI 1998. 04. 18. Repüléstudomány Közlemények X. évfolyam 24. szám pp. 165-173 ZMNE Szolnok 1998.
7. Szilágyi D, *„Rotorlapátok légerőterhelésének meghatározásához szükséges adatok méréssel történő meghatározása”* XVII. Repüléstudományi Konferencia Szolnok, ZMNE RTI 2000. 04. 15. Repüléstudomány Közlemények XII. évfolyam 29. szám pp. 165-173 ZMNE Szolnok 2000.
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9. Szilágyi D, *„Koaxiális Rotorok Aerodinamikai Modellezése*” A Katonai Rendszerek Repülőgépei, a Katonai Repülőgépek Rendszerei c. Repüléstudományi Konferencia Szolnok, ZMNE-RTI 2003. 04. 04. CD-ROM ZMNE Szolnok 2003.

Works are not valuable as publication:
Szilágyi D, *„Rotorlapátok Légerőterheléseinek Dinamikai Vizsgálata”* poszter MTA AMB 1999. évi Kutatási és Fejlesztési Tanácskozás Gödöllő 1999. 01. 25.
Dr. Gausz T.-Szilágyi D, *„Aerodynamic Loads of Helicopter Rotor Blades”* 3rd International Conference of Unconventional Flight Siófok 2001.09.12.-14.

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