COMPREHENSIVE MODELLING OF SMART STRUCTURES FOR AEROELASTIC APPLICATIONS

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Abstract

The paper presents the results of activities in Helicopter Mechanic Group at Warsaw University of Technology concerning modelling of smart structures for rotorcraft application. Two computer models were used: comprehensive rotor blade model and typical cross section approach. The aerodynamic model for aerofoil with trailing edge flap performing arbitrary motion was developed and included into analysis. Application of two control algorithms in the time domain to control helicopter rotor blade using „smart devices" are presented. The first algorithm uses deterministic learning control technique, and the second, heuristic one, used for rotor optimisation utilises two control variables. Both methods were efficient in computer simulation fulfilling the required tasks.

The combined application of the new unsteady aerodynamic loads calculation model and control algorithm in the time domain proved to be effective, giving reasonable results.

The further investigation should concern inclusion electromechanical model of sensing/actuating element into model of rotor blade with active device for investigation the properties of complete servoaeroelastic system.

The results of this research form basis for designing experimental facilities and research confirming the properties of aeroelastic systems.

1 Introduction

During the recent decade the interest in smart structures application varied from scepticism to enthusiasm, actually stabilising as the mature research topic with serious prospects of implementation in practice [1].

The idea of "smart" or "intelligent" structures stems from an attempt to design and manufacture a simple and compact system which would recognise the changes in the environment, analyse the situation, make the decision and react in a reasonable way. The idea corresponds to observation of living creatures which, to survive, adapt to variation of environment. The latest achievements in material science, electronics, micromechanics and computer sciences led to a feasibility of the concept and a variety of prospective applications is expected and investigated [2]. The vital activity is going on in aerospace and aeronautics, both in fixed and rotary wing field [3].

Different ways of putting the idea of smart structures into practice can be classified as *intelligent materials, passive systems and active systems*. Intelligent materials would monitor, make decision and respond to external stimulus on the molecular or "cell" level. Artificial intelligent materials are under development and the most promising concepts seem to be "perceptive composites".

In *smart passive systems* acting stimulus cause the counteraction to external stimulus due to structure design without dedicated supply of force or energy for control. "Aeroelastic tailoring" in aeronautics is a good example of this approach.

Intelligent active systems can be regarded as a generalisation of controlled structures, which contain sensors and actuators linked to the processor. Typical components of an intelligent active system are a host structure, a network of sensors, a network of actuators and capabilities of real-time control. An intelligent active structure, which reacts by changing its mechanical properties, is named an *adaptive structure*.

In prospective smart structures actuators, sensors and processors would be integrated within the structure and have structural functionality. Up till now, usually separate devices provide sensing, actuating and control.

From the late 1980's concepts of smart structures are widely explored in both fixed- and rotary-wing aircraft technology. Intelligent devices are investigated for application in different parts of aircraft (such as fuselage, wings, undercarriage, engines, avionics) for achieving various tasks, like reduction of vibration and noise level, performance improvement, health and usage monitoring, etc.

In this paper modelling of smart structures for application in aeronautics is presented. The main representative of aircraft, due to the author's interest, is rotorcraft, mainly helicopter, which forms a challenging task for smart structure applications.

The problem addressed in this study is the modelling of smart system for numerical simulations to provide reliable evaluation of different design concept.

2 Smart structures in rotorcraft technology

Application of smart structure concept to improve behaviour of helicopter rotor is being investigated for several recent years. The long term objective of smart structure application to improve helicopter rotor is to replace the complicated mechanism of swash plate and hub by various adaptive structure type elements. It will reduce total number of parts and will allow application of active control for reduction of vibration/noise level or improvement of the overall rotor performance.

A variety of practical concepts are considered and investigated in many research centres and universities (Fig.1). Each of these concepts has advantages and drawbacks, but two seem to be the most promising: actively controlled devices mounted on the blade, such as a trailing edge flap and shape adaptive blades.

The main difficulty in practical realisation of a tab mounted at the blade trailing edge is to design a driving mechanism, which would work at the blade in rotating and periodically varying environment as well as to choose a proper control strategy. For shape control of a blade, all problems concerning active composites and aeroelastic tailoring should be considered.

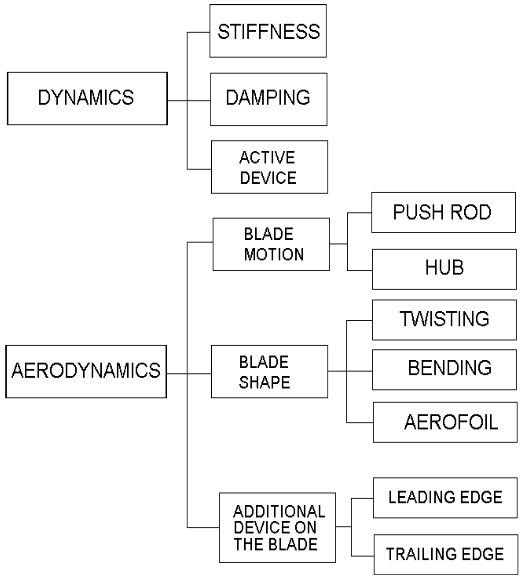

Fig.1. Concepts for influencing helicopter rotor behaviour

These concepts influence mainly aerodynamic loads acting on the blade, and due to aeroelastic couplings, modify behaviour of the rotor. The other important aspect is a control algorithm, which should be effective for nonlinear systems, and in rotorcraft case for systems periodically varying in time. The best, widely applied way of getting insight into the influence of the additional control of aeroelastic system is numerical simulation, which utilises an adequate physical and mathematical model of the investigated phenomena.

3 Comprehensive "smart blade" model

„Smart rotor blade" is an actively controlled system, which consists of three main parts (Fig.2)

- plant to be controlled (rotor blade),
- observer to measure the state of the plant (sensors for identification)
- control unit with proper algorithm to obtain control signals based on observer measurements.

Modelling of each subsystem is a difficult task, due to inherent nonlinearities in aeroelastic rotor phenomena.

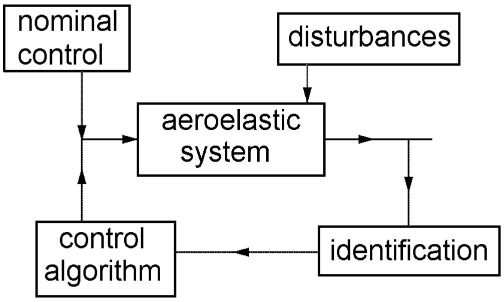

Fig.2. General controlled system

Application of smart structure concept to aeroelastic system is based on adding the sensing / actuating element performing according to control algorithm. Usually modification of aeroelastic system influences all kind of loads involved: aerodynamic, inertia and elastic. The dynamics of control device, very often ignored in control analysis, should also be taken into account.

The blade forms an unsteady, periodically excited aeroelastic system, where the main loads are aerodynamic, elastic and inertia. The model of the aeroelastic smart rotor should be composed of the elements like blade structure, proper aerodynamic loads, embedded smart active flap or other additional control devices with its own dynamic and control algorithm.

For computer modeling of aeroelastic phenomena, the model of the system should be as detailed as possible to describe new, or predict old "instabilities". But for control system verification the model may be less detailed, as the control usually has some degree of possible adjustment to situation.

3.1 Blade structure models

In rotorcraft community various inhouse and commercial codes exist, which are adapted to model smart rotor behaviour [4, 5].

In Warsaw University of Technology, Helicopter Mechanic Group at Institute of Aeronautics and Applied Mechanics the general, computer model was developed for helicopter rotor blade investigation [6] allowing modelling of various hub and blade designs and modification to capture smart rotor behaviour.

A helicopter rotor in steady flight is considered assuming constant angular velocity Ω of the rotor shaft. The model (Fig.3) allows to include into analysis all hinge arrangements and blade deflections.

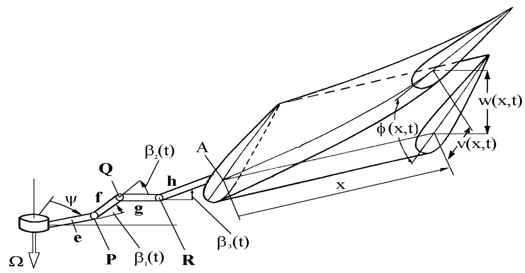

Fig. 3. General model of the blade

A blade attachment to the rotor shaft can be composed in many different ways including from none to three hinges in arbitrary sequence and up to four stiff segments to allow for different hinge placement within the hub. Blade pitch control angle $\theta(t)$ is added to the rotation in pitch hinge. The rigid or elastic blade is attached to the hub. The blade is treated as a beam having arbitrary planform along the span, and may be geometrically twisted about the straight longitudinal elastic axis. A deformable blade may twist itself about its elastic axis and bend in two directions perpendicular to it. The blade deflections are considered small and its curvature moderate. Blade elastic loads are derived assuming that there is no section warping.

The blade displacement vector is comprised of two groups of variables: elastic degrees of freedom resulting from discretization of blade deflections by free vibration, rotating modes and rigid degrees of freedom corresponding to the rotations about the hinges.

The equations of motion were obtained from Hamilton's principle and the most of the algebraic manipulations were transferred to the computer program.

In some preliminary studies [7] the typical cross section approach was also utilised. In this kind of study an aerofoil with tab in a pulsating stream (Fig.4) is explored as an aeroelastic system at which a new aerodynamic model or control strategy is applied. This simple „typical cross section" model is used for obtaining insight into the phenomena considered.

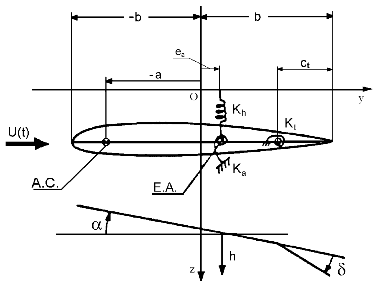

Fig.4. Typical cross section approach for modelling blade with trailing edge flap

3.2 Models of aerodynamic loads

Aerodynamic loads play essential role in behaviour of aeroelastic system. Evaluation of aerodynamic loads on a main or a tail rotor should take into account, that components of flow velocity along and perpendicular to a blade chord are composed of contributions from shaft angular rotation, forward flight velocity, blade and hub elastic deformations and/or rotations in hub hinges. The flow velocity and blade section angle of incidence can vary in an arbitrary way as functions of time, within a broad range, including stall.

A method for aerodynamic load calculation in rotorcraft aeroservoelastic problems should cover: *three components of loads*: lift, drag and moment, *arbitrary* variations in time of: angle of attack (incidence) up to deep stall, translations perpendicular to and along the chord, fluctuations of free stream velocity, shape of blade wakes, and, which has become important recently, arbitrary motion of additional control devices (flaps, tabs).

The method of calculations should be compatible with existing computer codes for simulation and stability analysis of rotorcraft. Ordinary differential equations are widely applied in helicopter rotor aeroelasticity for calculation of steady motion as well as for Floquet or eigen-values for stability evaluation, and gains in control algorithms.

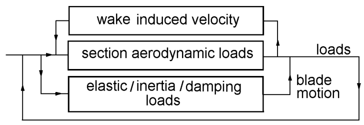

Fig.5. Flow decomposition for a 2-D model

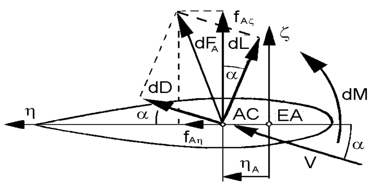

Fig.6 . Aerodynamic loads on a blade section

But a practical method for rotorcraft application needs not to be *too* general. Up till now the assumption of a two-dimensional flow environment has been well justified (Fig.5 & 6).

A new challenge is calculation of unsteady loads on blade with trailing edge flap. Despite the latest achievements in CFD, the capability of solving full equations of flow around an aerofoil in arbitrary motion is still unpractical. The way to avoid some of these time consuming methods is to express the flow motion by ordinary differential equations in state variables - these methods can account for arbitrary aerofoil motion, and capture the history of flow inherent to unsteady aerodynamics.

The method for calculating aerodynamic loads in rotorcraft activity are being developed somehow along to fixed wing activity, due to some peculiarities of rotor flow and vortex shape, but as far as additional blade devices are concerned, in this case the methods from fixed - wing field are widely adopted.

The methods for calculating unsteady aerodynamic loads on an aerofoil with a trailing edge tab were developed as the response to the needs of current designs. The progress driving force can be attributed (in chronological order) to lift augmentation (steady loads) and preventing aileron (tab) flutter (unsteady), transonic buzz, active flutter suppression systems and now smart structure technology.

Initially, unsteady aerofoil methods utilised in smart structures were usually extensions or adaptations of fixed wing cases, such as [9]. Next the special methods emerged [10 - 12].

The model used in this study was developed in [13]. It concerns a thin, low cambered aerofoil with a flap at the trailing edge in inviscid, incompressible, two-dimensional flow. (Fig.7).

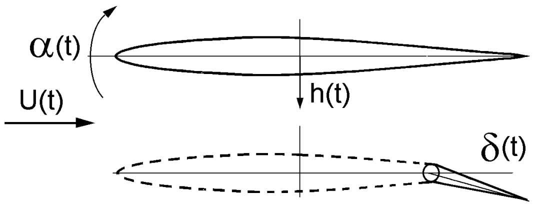

Fig.7. Thin aerofoil with a trailing edge flap.

Both aerofoil and flap perform arbitrary motions, which may be different functions of time, so free stream velocity *U(t)*, aerofoil angle of incidence $\alpha(t)$ and angle of tab deflection $\delta(t)$ may depend on time in different ways, not exceeding values at which flow separation occurs.

Solution follows the approach of potential of the perturbation velocity, which fulfils the Laplace equation with proper boundary conditions. The integral equation for bound circulation is solved by Fourier series decomposition, and then having the velocity potential calculated, the differential pressure on the aerofoil is obtained from the linearized Bernoulli equation. Lift and moment on aerofoil and flap are calculated by integrating the pressure distributions along the chord.

Total unsteady loads (both lift and moment) are calculated as the sums of contributions from the aerofoil itself and the tab.

This result have been achieved by decomposition of loads on aerofoil and tab based on a velocity criterion, which differs this approach from the previous works based on spatial decomposition. The aerodynamic loads described here as "aerofoil" result from the main aerofoil velocities along the full chord length (tab included). The "tab" loads stem from contributions resulting from the velocity variation due to tab motion relative to the aerofoil.

The result of this approach is that the same general expressions for calculating contributions to loads from the aerofoil and from the tab are derived. The method was validated using the Theodorsen wake model.

3.3 Control algorithm

In a general form helicopter rotor blade is inherently a nonlinear system, varying periodically in time. This periodic variations stems from primary blade control for achieving the desired flight conditions, usually in the form of changes of blade pitch angle in the form:

$$\theta(t) = \theta_0 + \theta_1 \cos(\Omega t) + \theta_2 \sin(\Omega t) \qquad (1)$$

which causes blade rigid or elastic flapping:

$$\beta(t) = \beta_0 + \beta_1 \cos(\Omega t) + \beta_2 \sin(\Omega t) \qquad (2)$$

There are a few (if any ?) methods effectively dealing with such kind of systems. This was the reason for searching „nonclassical control methods” to apply in the considered case. In [7] the learning control was applied for the first time to rotor blade and proved to be effective. This was the reason for more detailed consideration of learning control methods.

The term learning control was introduced for controlling plants which perform repetitive tasks to underline, that „information from the previous trial of the plant dynamics and the tracking error at each time step is reflected in the next trial” [14]. The other terms describing this kind of control are „repetitive control", „iterative control" or „betterment process". So such controllers „learn from the previous experience performing a specific command to improve their performance in the next execution of the command" [7].

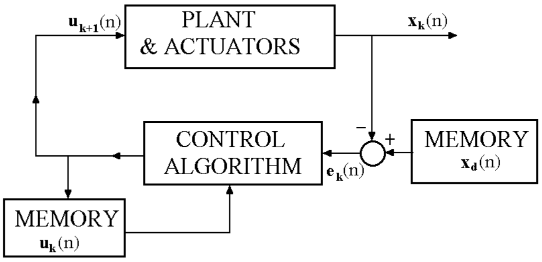

Fig.8. Learning control algorithm.

The principle of learning control is illustrated in Fig.8. The subsequent control inputs depends both on the prescribed (required) behaviour of the system and the control in the previous period, both in the same on in other time steps within the time period. The difference of the actual and required system output is given by the error $\mathbf{e}_i(k)$ defined as

$$\mathrm{e}_i(k) = \mathrm{x}_d(k) - \mathrm{x}_i(k) \tag{3}$$

where the subscript i describes the actual period of time and k is the step within the period.

The general form of the control may be written as

$$\mathbf{u}_j = \mathbf{u}_{j-1} + \mathrm{L}\left(\mathrm{e}_{j-1}\right) \tag{4}$$

where $\mathrm{L}\left(\mathrm{e}_{j-1}\right)$ is a learning control operator acting on the system output error (3).

The learning operator may have different forms, for instance

$$\mathbf{u}_j = \mathbf{u}_{j-1} + \mathrm{L}\mathrm{e}_{j-1} + \mathrm{F}\int \mathrm{e}_{j-1}dt$$

$$\mathbf{u}_j = \mathbf{u}_{j-1} + \frac{d^j}{dt^j}\mathrm{e}_{j-1} \tag{5}$$

$$\mathbf{u}_j = \mathbf{u}_{j-1} + \mathrm{L}\mathrm{e}_{j-1}(k+1)$$

The learning operators should provide, that the control forms a contracting mapping, fulfilling the convergence condition

$$\left\|\mathbf{e}_{i+1}\right\|_\lambda \le \rho\left\|\mathbf{e}_0\right\|_\lambda \to 0, \text{if } \ \mathrm{i} \to \infty \tag{6}$$

The mathematical model of a helicopter rotor blade in the form of nonlinear system of ordinary differential equations periodic with respect to time, with a scalar control *u(t)* corresponding to the angle of deflection of the trailing edge tab

$$\dot{\mathbf{x}} = \mathbf{f}(t, \mathbf{x}, u) \tag{7}$$

was linearized about the desired motion $\mathbf{x}_d(t)$:

$$\dot{\mathbf{x}} = \mathbf{A}(\mathbf{t})\mathbf{x} + \mathbf{B}(t)u(t) + \mathbf{R}(\mathbf{x}, \mathbf{x}_d, u(t), u_d(t), t) \tag{8}$$

$$\mathbf{A} = [A_{ij}] = \left[\frac{\partial\ f_i}{\partial\ \mathrm{x}_j}\right]_{\mathbf{x_d}, u_d}, \mathbf{B} = [B_i] = \left[\frac{\partial\ f_i}{\partial\ \mathrm{u}}\right]_{\mathbf{x_d}, u_d}$$

and discretized with respect to time using approximating the time derivative by the forward finite difference

$$\dot{\mathbf{x}} = \frac{\mathbf{x}(t+\Delta t) - \mathbf{x}(t)}{\Delta t} \tag{9}$$

Inserting (9) into (8) transfered the linearized equation to the discrete time domain

$$\begin{aligned}\mathbf{x}(t+\Delta t) &= [\mathbf{I} + \mathbf{A}(t)\Delta t]\mathbf{x} + \mathbf{B}(t)\Delta t u(t) + \\ &+ \mathbf{R}(\mathbf{x}, \mathbf{x}_d, u(t), u_d(t), t)\Delta t\end{aligned} \tag{10}$$

These two operation i.e. linearisation and discretization are needed for transferring the system to the form

$$\mathbf{x}(k+1) = \mathbf{C}(k)\mathbf{x}(k) + \mathbf{D}(k)u(k) + \mathbf{d}(k) \tag{11}$$

It was showed in [14], that the control defined as

$$\begin{aligned}&u_{i+1}(k) = u_i(k) + \lambda[\hat{\mathbf{D}}_i^+(k) : -\hat{\mathbf{D}}_i^+(k)\hat{\mathbf{C}}_i(k)]\times \\ &\times[\mathbf{e_i}(k+1)^T : \mathbf{e}_\mathbf{i}^\mathbf{T}(k)]^T \\ &\mathbf{e}_i(k) = \mathbf{x}_d(k) - \mathbf{x}_i(k)\end{aligned} \tag{12}$$

fulfils the learning condition if, for initial error $\mathbf{e}_i(\mathbf{0}) = \mathbf{0}$, the estimate of matrix **D**(*k*) satisfies the condition

$$\left|1 - \lambda \,\hat{\mathbf{D}}_i^+(k)\mathbf{D}(k)\right| < 1 \qquad (13)$$

The algorithm was applied to obtain the required motion of a helicopter rotor blade hingeless blade stiff in bending and elastic in torsion. The objective of the control application was to suppress the prescribed harmonics of steady motion. As the first result of numerical simulation it was found that due to high fundamental torsional frequency of the blade, a tab of chord 0.1c, which can influence blade twisting deflection should elongate from 23.3% to 95% of the blade span.

The control constant λ in (9) should be adjusted by trial and errors and in the case considered, the smallest value of λ which was found to be effective was 0.05.

For the chosen tab chord and control parameter, the sample results of blade control are given in the figures for helicopter advance ratios of 0.15 and 0.35. These show the motion of the nonlinear system after 10 rotations (which is regarded as the blade steady motion), the required motion for the case considered and the controlled motion after 10 rotations of the algorithm being applied.

Different form of "learning control was applied for "typical cross section" model In these numerical simulations, the periodic excitation come from flow velocity variation according the function typical for rotor blade principal excitation:

$$U(t) = U_0\left[1 + \sin(\Omega t)\right] \qquad (14)$$

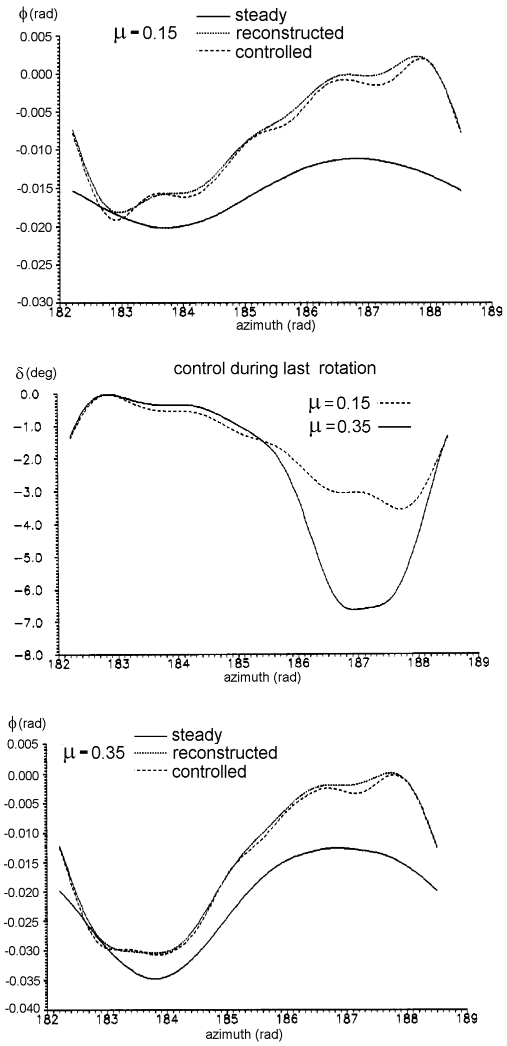

Fig.10. Required motion obtained by control algorithm.

The objective of the control strategy considered in that study was to influence the blade motion directly in the time domain. Different tab deflections were investigated, and rational reactions of the system were observed.

3.4 Rotor performance improvement

The heuristic control for rotor performance optimisation using flap at the blade trailing edge was developed in [15]. The effectiveness of controlling blade behaviour by two variables: pitch angle and angle of tab deflection in the time domain was shown. The simple control, proportional to the output was applied. The aerodynamic model was modified and extended ONERA model for aerofoil with tab.

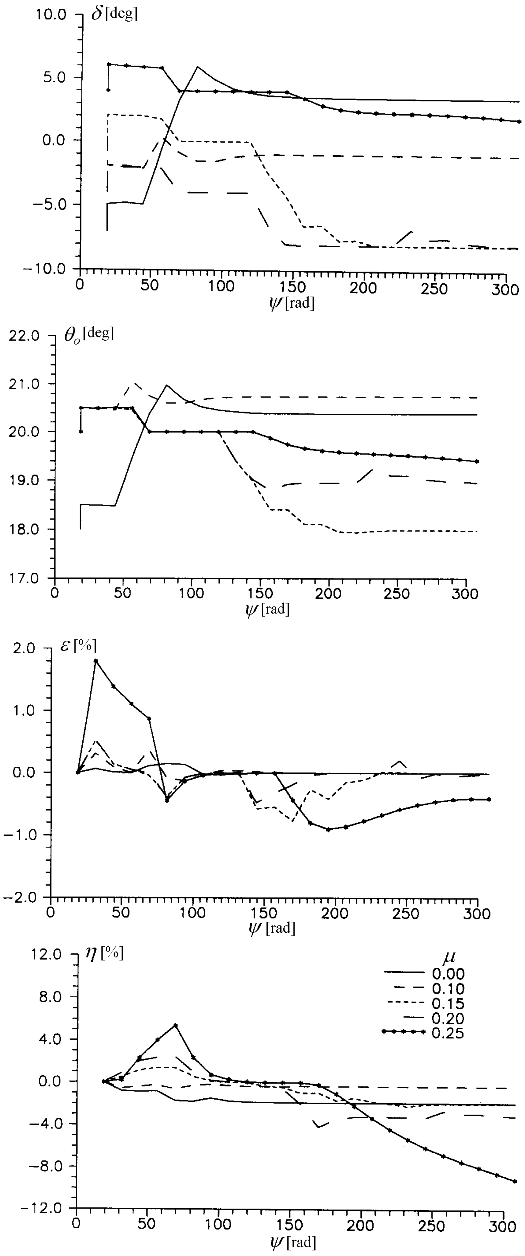

Fig.11. Results of rotor performance optimisation using two control variables.

The goal of the control was to minimise the blade performance index defined as

$$\eta = \frac{C_{Mz} - C_{Mz0}}{C_T} \tag{15}$$

where C_{Mz} is rotor torque moment coefficient and C_T is the rotor thrust coefficient.

During optimisation process the thrust was monitored and kept constant.

The algorithm constructed utilises two control variables: blade collective pitch angle θ_0 and tab deflection angle δ. The algorithm consists of two parts: *thrust stabilisation* by tab deflection and *minimisation of the blade torque moment* by using blade collective pitch. The sample results of calculations are given in Fig. 11, where ε is recursion of thrust value from the required value.

4 Active element modelling

The purpose of sensors is to acquire and identify information. In design of smart structure commercially available sensors (strain gauges both foil and semiconductor type, fibre optics, thermocouples, etc.) can be applied.

The main task performed by actuators is changing properties of the structure according to a control signal. The actuator transfers signal of one form of energy (usually an electrical one) into the other one (to mechanical action - strain or displacement) in a way opposite to sensor. In adaptive structures the actuator task is to convert signal in the structure. For these applications solid state actuators are investigated extensively, due to their design simplicity.

The vital part of smart structure is sensing/actuating element. To obtain sensing/actuating capability, materials with an ability of coupling different physical interactions (usually mechanical stress and electrical field) are considered. Cross-coupling effects manifest themselves as off-diagonal terms in such constitutive equations.

Prospective "smart materials" can be passive, reactive or intelligent *Passive materials* change their properties under external stimuli, but cannot transfer energy to the host structure. They can be applied only for sensing purposes. The glass fibres used in fibre optics are an example. *Reactive materials* change their properties in such a way that the energy can be supplied to the structure. They are used for actuating purposes. *Intelligent (smart) materials* can act both as the sensing and actuating devices.

Very promising materials for prospective „intelligent" applications are composites containing reactive materials like piezoelectric or shape memory alloys. It is expected to be possible to tailor properties of these materials according to the requirements and needs of particular structure.

The effectiveness of actuators depends also on the proper embedding it into host structure. To calculate actuator influence on host structure, a detailed analysis should be done, taking into account: constitutive relations of the actuator, deformation field caused by local strain, and imposition of equilibrium. Simplified analysis can give insight into a general performance of an actuator.

In [18] the simple example of one-stroke actuator was considered, showing, that the maximum useful work is available in the case, when mechanical compliance of the actuator and the structure are equal - the situation, which obviously is not always possible.

The actuator strain, which can be converted into strain in a host structure, depends on the way the actuator is placed in the structure, which influences stress distribution both in the structure and the actuator.

The piezoelectric (electroscrictive) phenomena seem to be the most suitable effects for sensor/actuator integration activity.

For evaluation of efficiency of energy transfer the transducer electrical model shown in Fig.12 was considered in [17] and [18].

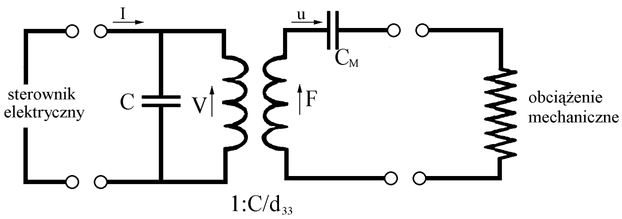

Fig. 12. Electromechanical model of piezoelectric active element.

The relations between electrical properties and signal were developed for pezoelectric block and the experimental evaluation of parameters by application into Wheatstone bridge is presented.

The evaluation and experimental validation of electrical properties of actuator was also possible.

Conclusions

The paper presents the results of activities undertaken up till now in Helicopter Mechanic Group at Warsaw University of Technology for modelling of smart structures for rotorcraft application.

Two models are used: comprehensive rotor blade model and typical cross section approach. The aerodynamic model for aerofoil with trailing edge flap performing arbitrary motion was developed and utilised.

The attempts of application of control algorithms in *the time domain* to control helicopter rotor blade using „smart devices" are presented. The first algorithm applied new learning control technique, and the second used for rotor optimisation utilised two control variables. In computer simulation both methods were efficient fulfilling the required tasks.

The combined application of the new unsteady aerodynamic loads calculation model and control algorithm in the time domain proved to be effective, giving reasonable results.

The further investigation will concern inclusion of both methods into rotor blade model with tab dynamics combined with electromechanical model of active element enriching system model.

The results of this research form basis for designing experimental facilities and research confirming the properties of aeroelastic systems.

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