MODELLING ASPECTS OF ROTOR BLADE MOTION CONTROL VIA TRAILING EDGE TAB

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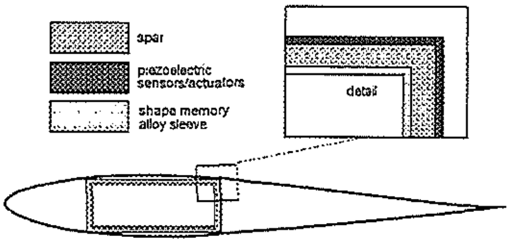
Abstract

Selected aspects of application of a tab at a trailing edge of a rotor blade are discussed including modelling of aerodynamic loads, formulation of mathematical model of rotor/tab/driving mechanism, selected non-standard control strategies and influence of blade motion on tab driving mechanism. These subjects should be addressed more deeply in comprehensive rotor/tab analysis.

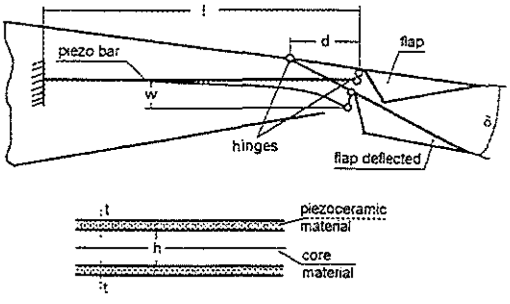
Introduction

In rotorcraft, as well as in fixed wing smart structure technology can be applied within different part of aircraft: fuselage, avionics, engines. For helicopters the main effort in this field is devoted to improve rotor behaviour. Rather non-adequate properties of existing active materials, give prospects of application of smart structure concept mainly for additional rotor control.

Several design ideas proposed by different authors for application of smart materials in rotor control were considered; them Two of the most promising concepts, presented in Fig.1 [1], seem to be active control of blade shape and operating a tab mounted at blade trailing edge. The later concept is considered in this paper.



a) deflecting blade



b) trailing edge tab

Fig. 1. Two smart structure concepts for rotor control

The leading example of tab application are Kaman helicopters using tabs for primary control proving that such blade mounted device is effective.

Application of active materials can lead to compact, reliable driving mechanism for tab deflection, so from the beginning the main objective of research is to design an effective tab deflecting device [2].

Feasibility studies carried up till now showed promising results concerning application of blade mounted trailing edge tabs for improvement of helicopter rotor behaviour. The main objectives investigated are vibration suppression and noise reduction by avoiding unfavourable BVI effects, although other tasks such as performance improvement were also studied.

First, the concepts in Fig.1 were analysed using rather simple engineering approach, the excellent example is [3]. Recently more comprehensive analysis are done concerning the influence of the tab on blade motion [4] and also dynamic of the tab [5].

The main difficulty in evaluating blade/tab system performance arise from still unsettled properties of tab driving mechanism, as different design concept are under consideration.

In this paper selected research topics concerning tab application are reviewed with emphasis on multidisciplinary aspects of tab operation and modelling. A generic approach is proposed to investigate complex blade/tab aeroservoelastic system. The calculated results were obtained using the individual blade model [6] extended to include the effects considered.

Aeroservoelastic system

An actively controlled system is composed of two main parts:

- plant to be controlled
- control system in which there can be distinguished
  - observer to measure the state of the plant
  - control unit to obtain controls based on observer measurements.

In rotorcraft technology an aeroelastic system with time varying parameters is controlled. Variation of system parameters comes from both time dependent flow phenomena and periodic primary rotor control.

In Fig.2. the general scheme for controlled system adapted to rotorcraft case is shown. The control process is separated into primary and additional controls. Active elements are these part of the system, where conversion of different kind of energy takes place; the „control energy" (electrical, thermal, magnetic) is converted into mechanical action. These elements form interfaces between additional control and the structure.

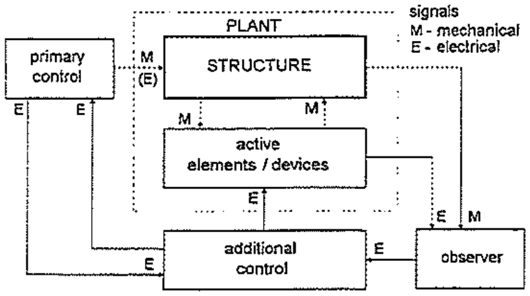


Fig.2. Rotor control of based on „smart" elements

Plant modelling

Rotor behaviour is determined by influence of three kind of loadings:

- aerodynamic
- elastic
- inertia

During the progress in helicopter technology, well validated models have been developed describing aeroelastic and aeromechanical phenomena. It is natural, that they are being modified to investigate effects of incorporation of smart elements into rotor systems. Mounting controlled trailing edge tab on rotor blades influences different parts of model to different extend.

The base change is enlarging number of variables (control states or/and degrees of freedom) of the model by at least one - tab deflection.

Blade inertia loads are influenced in terms of changing values of generalised masses and moments of inertia. Unless tab itself and its driving mechanism are very heavy, their influence on blade inertia matrix is insignificant.

The presence of tab does not change blade elastic loads.

Aerodynamic loads are influenced the most by the tab operation. The presence of tab changes significantly the flow around the part of the blade, where it is mounted. This should be reflected in method of calculating aerodynamic loads Such methods are currently under extensive development and are discussed in the next chapter.

The equation of motion for tab can be added into the system covering the mutual interference between a tab and a blade motion. The special part of plant is tab driving mechanism. Its placing on the blade may change blade inertia properties and also its operating properties may be influenced by blade motion. Modelling of driving mechanism depends of the design concept utilised.

Control methods

For rotor operation two kinds of control are applied. The primary control is needed for performing required flight state. The additional control can be added to improve the overall rotor behaviour.

Although the long term goal of prospective smart structure application can be integrating rotor primary and additional control into one system [7], up till now these two control strategies are applied separately.

Additional control can be included to achieve various objectives:

- improvement of the overall rotor performance,
- vibration suppression and noise reduction,
- influencing blade motion in a particular way.

The control law and algorithm should be adjusted to the objectives.

In the following sections the selected topics of modelling of „a smart rotor" with a trailing edge tab are addressed in more detail, especially: modelling of aerodynamic loads, formulation of mathematical model, control strategies applied, influence of blade motion on tab driving mechanism..

Modelling of aerodynamic loads

A method for aerodynamic load calculation in rotorcraft aeroservoelastic problems should cover: three load components (lift, drag and moment), arbitrary motion of aerofoil and tab and should be compatible with existing computer codes for rotorcraft simulation and stability analysis.

In the past the vast amount of rotorcraft aeroelastic analysis was done using strip theory and two dimensional static aerofoil coefficients with some kind of global expressions for rotor inflow. These assumptions have been justified by validation with experimental data. So it can be supposed that a practical method for calculation tab aerodynamic loads need not to be *too* general.

The boundaries of flow parameters to be covered can be evaluated using sample rotor data.

- Tab can be placed: from 0.2R (outside hub elements) to 0.95R (up to modern advanced tips)
- Resultant flow velocity come from shaft rotation U_T=220m/s and forward flight speed V_{max}=84m/s, which gives maximum tip speed of U_{max}=300m/s, and M_{max}=0.9
- Reduced frequency based on rotor angular velocity is

$$k = \frac{\omega c}{2U} = \frac{\Omega c}{2\Omega r} = \frac{c}{2r} \in \left(0.04 \div 0.14\right) \qquad (1)$$

So the range of blade flow parameters is

$$k \in \left(0.04 \div 0.14\right) \;\; M \in \left(0.9 \div 0\right) \qquad (2)$$

Due to some peculiarities of rotor flow and vortex shape methods for calculating aerodynamic loads in rotorcraft were developed somehow parallely to methods for fixed wing. But for tabs mounted at the blade trailing edge, fixed - wing methods are widely adopted.

As during this study, it occurred unsuccessful to find specific overview of methods for calculating unsteady aerodynamic loads on aerofoil with a trailing edge tab, it seems worth to overview briefly the references, in which the trailing edge flap/tab is considered.

Driving force for calculating unsteady aerodynamic loads on an aerofoil with a trailing edge tab was (in chronological order) lift augmentation, preventing aileron (tab) flutter, transonic buzz, active flutter suppression and currently smart structure technology.

The first papers dated to *thirties and forties* were devoted to investigation of lift augmenting systems; the overview of static aerofoil/tab data with list of references can be found in [8-10].

In the same time, the unsteady methods were developed for investigating possibility of flutter type instability of wings with ailerons flap/tab, mainly in the frequency domain. The classical approach for calculation of unsteady air loads on an aerofoil with a trailing edge tab for subsonic, incompressible flow was developed by Theodorsen [11] and next extended by Theodorsen and Garrick to wing aileron-tab configuration. [12]. Some papers such as [13] concern only aerodynamic derivatives. The restrictions of these approaches included constant flow velocity, no chordwise aerofoil motion and the same motion of aerofoil and tab. Greenberg's [14] extension of these methods covered the varying free stream velocity, but not the tab deflection.

In the *fifties* a lot of effort was spent to unsteady, transonic loads, due to the need for preventing transonic buzz [15,16]. The experimental works in NLR (the Netherlands) [17] should be quoted here.

For fixed wings, unsteady aerofoil aerodynamics is usually formulated *in the frequency domain*. This formulation suites these phenomena where one discrete frequency plays the major role. It is generally not a case in rotary wing, where, due to periodic excitation, there is no defined frequency of instability.

In *sixties and seventies* active flutter suppression systems evoked the need for covering arbitrary tab motion. The papers [18,19] are devoted to arbitrary tab motion relative to fixed aerofoil. The method of transformation to the time domain applied for instance in [20] released constraints of harmonic motion.

Now the main need for considering of arbitrary motion of an aerofoil with a tab stems from rotorcraft activity due to prospective application of smart structures.

For arbitrary tab motion, the indicial function approach was investigated in [21-22]. The extension of method [14] was developed in [23]. In [24] previously developed state modelling using Theodorsen function was extended. An heuristic application of the ONERA stall model for deflecting tab was used in [25].

Most of the methods mentioned above utilise some experimental factors, included into model. It seems that within the range (2) of blade parameters, empirical corrections can improve correlation with experimental data. In Fig.3 results of application of corrections derived from experimental data to the method [26] is illustrated. Using only one additional variable improved correlation with experiment significantly.

The main difficulty in development of aerodynamic tab models is lack of experimental data within proper range of aerofoil and tab degrees of freedom and Mach number. It does not allow to validate the overall results of calculation.

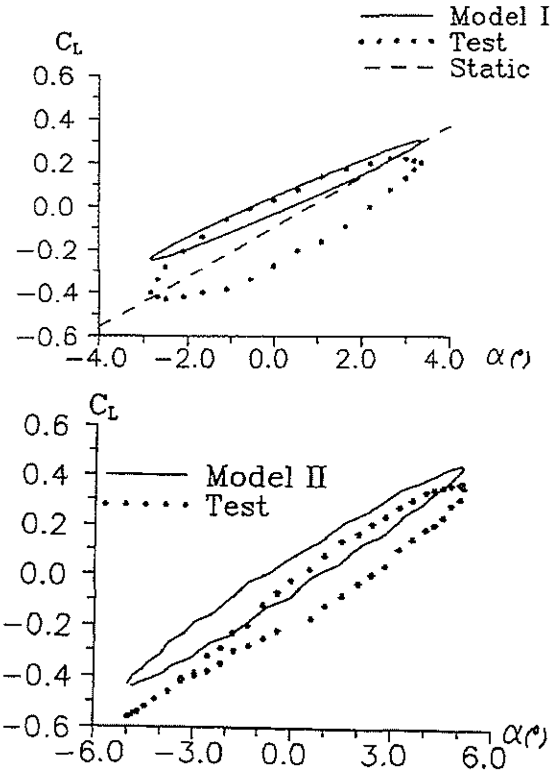


Fig.3. Influence of empirical corrections on correlation with experimental data. NACA 23010 aerofoil, no tab, k=0.125, Ma=0.4.

Mathematical model

To investigate control strategies the mathematical model should be formulated in a way compatible with control theory.. Usually a resulting rotor model consists of a set of nonlinear ordinary differential equations periodic with respect to time:

$$\dot{\mathbf{z}} = \mathbf{g}(t,\mathbf{z},\mathbf{u}) \qquad (3)$$
$$\mathbf{g}(t,\, \mathbf{z},\, \mathbf{u}) = \mathbf{g}(t + T,\, \mathbf{z},\, \mathbf{u})$$

The function $\mathbf{g}(t,\mathbf{z},\mathbf{u})$ fulfils conditions for existence and uniqueness of solution of the system (3). Under nominal (primary) control vector $\mathbf{u}_D(t)$, the system should perform a periodic, nominal motion $\mathbf{z}_D(t)$

This nominal rotor motion may be obtained from such considerations as for instance the way of vibration reduction, blade stability augmentation etc. In such a case the functions $\mathbf{z}_D(t)$ and $\mathbf{u}_D(t)$ may not fulfil (3). The disturbed motion $\mathbf{x}(t)$ of the system is defined as:

$$\mathbf{x}(t) = \mathbf{z}(t) - \mathbf{z}_D(t) \qquad (4)$$

Additional control is extracted from the overall *control vector* $\mathbf{u}(t)=\mathbf{u}(t)-\mathbf{u}_D(t)$ *and* (3) is transferred to the form:

$$\dot{\mathbf{x}} = \mathbf{f}(t,\mathbf{x},\mathbf{u}) + \mathbf{h}(\mathbf{t}) \qquad (5)$$

where

$$\mathbf{f} = (t,\mathbf{x},\mathbf{u}) = \mathbf{g}(t+T,\mathbf{z}_D+\mathbf{x},\mathbf{u}+\mathbf{u}_D),$$

$$\mathbf{h}(t) = -\dot{\mathbf{z}}_D \,(7)$$

The system (3) is also periodic with respect to time, but the nominal solution is $\mathbf{x}_D(t)=\mathbf{0}$

If the differences between the nominal blade motion $\mathbf{z}_D(t)$ and control $\mathbf{u}_D(t)$ and the actual $\mathbf{z}(t)$ and $\mathbf{u}(t)$ are small, the plant model can be approximated by the linearized equations:

$$\dot{\mathbf{x}} = \mathbf{A}(t)\mathbf{x} + \mathbf{B}(\mathbf{t})\mathbf{u} + \mathbf{d}(\mathbf{t}) \qquad (6)$$

$$\mathbf{A}(t) = \mathbf{A}(t+T) = [A_{ij}] = \left[\frac{\partial f_i}{\partial \mathrm{x}_j}\right]_{\mathbf{x}_d,u_d}$$

$$,\mathbf{B}(t) = \mathbf{B}(\mathbf{t}+\mathbf{T}) = [B_i] = \left[\frac{\partial f_i}{\partial \mathrm{u}}\right]_{\mathbf{x}_d,u_d}$$

$$\mathbf{d}(t) = -\dot{\mathbf{z}}_D(t) + \mathbf{f}(t,0,\mathbf{u}_0(t))$$

If nominal state values form the solution of nonlinear equations - the homogeneous system of linearized equations is obtained. If not - the periodic function of azimuth appears on the right hand side of linearized plant model. Usually it is difficult to find a solution of nonlinear model, so the second option is the case. The $\mathbf{d}(t)$ component in such a case can be treated as a bounded, time dependent disturbance.

Control strategies

A review of active control algorithms applied for additional control of helicopter rotors given in [27] identifies the fact, that the main activity is concentrated on application of LQC or LGC methods for linear model of the plant. The *parameters* of harmonic control variables (amplitudes and phases for prescribed frequencies) are adjusted to minimise the quality index:

$$J = \frac{1}{2}\int_t^{t+T} (\mathbf{x}^T\mathbf{Q}\mathbf{x} + \mathbf{u}^T\mathbf{R}\mathbf{u})dt \qquad (7)$$

Global and local, closed and opened loop approaches were tried and turned out to be effective both in computer simulations and *experiments for HHC and IBC.*

The wide application of these methods stems from the fact, that well developed theoretical background exists for controlling linear systems with constant state and control matrices. There are only a few efficient methods for periodic system (6) and almost none for nonlinear system (5).

The extension of LQC approach to time periodic systems was developed in [28] for model following type of control. The *methods for stabilisation of* blade motion developed in [29-30] are also promising.

Two new aspects of rotor control can be addressed here: whether the single input control is sufficient for rotorcraft needs and whether some non classic control approach can be utilised.

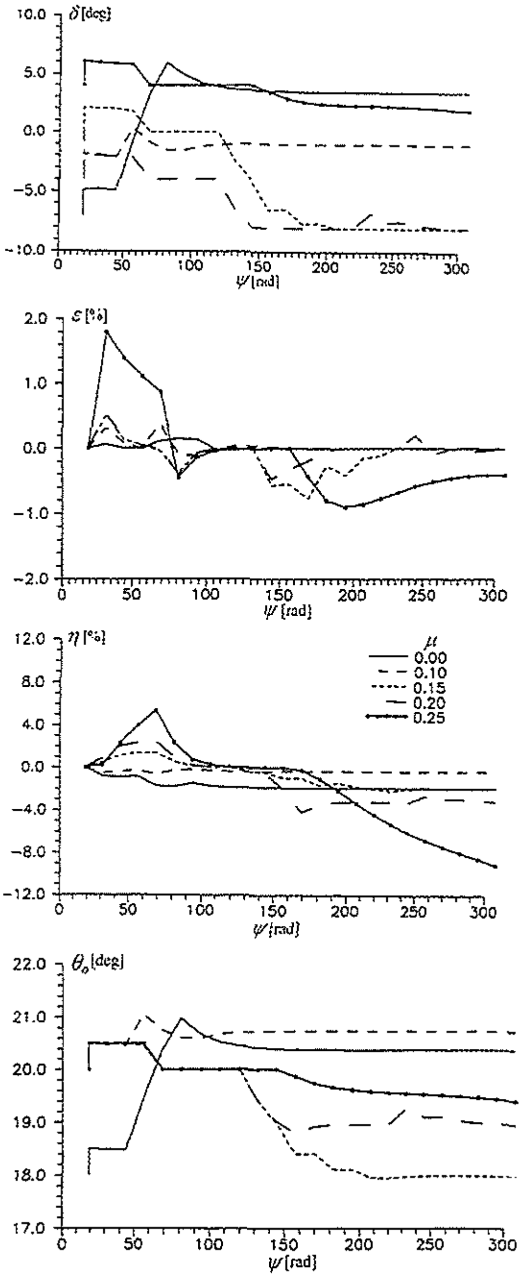


Fig.4. Rotor performance improvement using two controls: collective pitch and tab deflection.

In [25] the two level control was applied to minimise rotor torque: first level was stabilising the rotor thrust by blade pitch and the second was minimising the rotor torque moment by tab deflection. The results shown in Fig.4 concern rotor wind-tunnel trim. Tab deflection $\delta(\psi)$, collective pitch $\theta(\psi)$, nondimensional reduction in rotor torque $\eta(\psi)$ and thrust alleviation $\varepsilon(\psi)$ during control process are shown. Two control inputs strategy occurred to be effective for improving rotor performance..

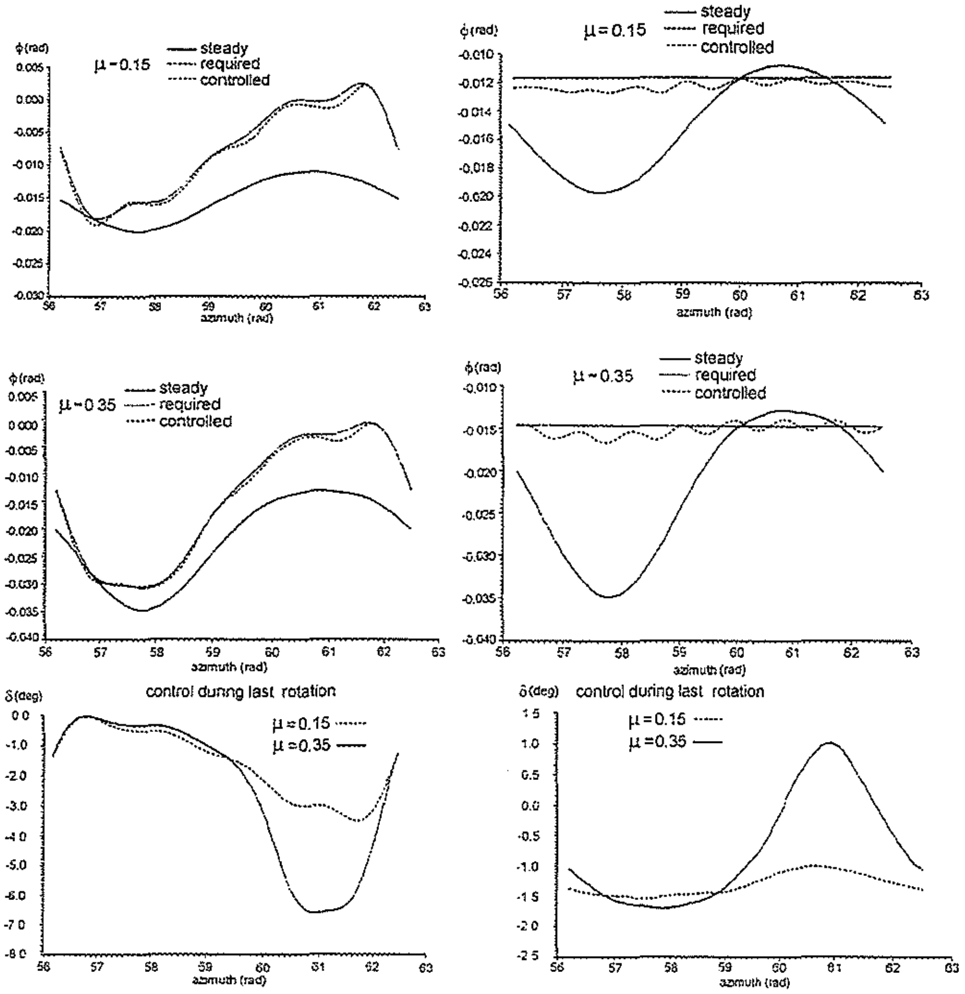


Fig.5. Results of application of learning algorithm for obtaining required blade motion

The second method was single input control using learning algorithm [31]. The results of application of the method are shown in Fig.5 for two cases: forcing required motion and suppressing disturbance. The blade twist angle $\phi(\psi)$, and tab deflection $\delta(\psi)$ during tenth rotation of control application prove efficiency of the method.

In this case numerical simulation showed, that it is possible to utilise effectively linear methodology to nonlinear case. The success of such approach can be attributed to moderate deviation of blade motion from required state during the controller activity.

The same results was obtained in [ ] for suppressing flapping variation by HHC method.

Influence of blade motion on tab driving mechanism

Tab which should be coupled with blade motion and the blade motion on the mechanism driving tab. The bender type mechanism (Fig.6) was considered [32].

The influence of blade motion on bender type driving mechanism (Fig.6) was explored showing (Fig.7) the great influence of time dependent flapping and pitch control on blade tip deflection $\phi_T(\psi)$ and bender tip deflection $w_T(\psi)$.

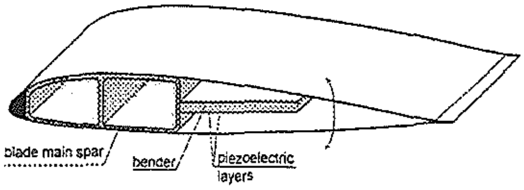


Fig.6. Bender excited by active layers mounted inside the blade.

Conclusions

Selected aspects of modelling rotor blade with trailing edge tab were discussed. For aerodynamic loads calculation at the present state of flow modelling, It seems sufficient to use 2D, unsteady inviscid flow model for the part of the blade, where the tab is mounted. The mathematical model of blade/tab/driving mechanism should be formulated in the way allowing application of modern control theories. Two new control methods one with two control states and the second using learning algorithm showed to be effective. In any design concept, influence of blade motion on tab driving mechanism should be accounted for, especially for full scale blades in forward flight

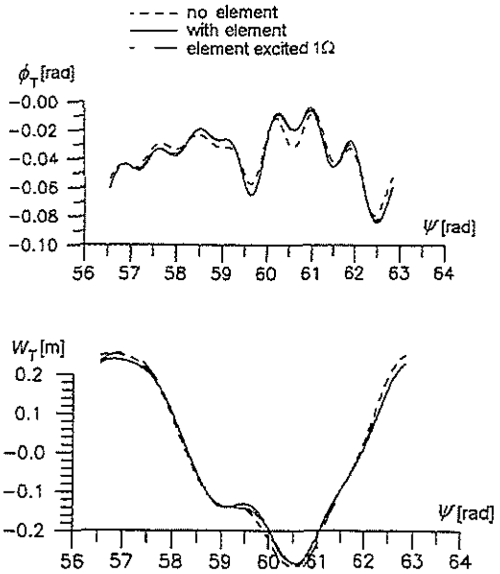


Fig.7. Influence of blade motion on bender performance

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