NEW ASPECTS OF HIGHER HARMONIC CONTROL AT A FOUR BLADED HINGELESS MODEL ROTOR

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Abstract

In order to investigate the effect of Higher Harmonic Control (HHC) at a hingeless rotor, a wind tunnel demonstration was performed which comprised open-loop as well as closed-loop tests. Whereas the open-loop tests aimed upon a systematical examination of the rotordynamics in the case of HHC control inputs, the main aspect of the closed-loop tests was the behaviour of the implemented adaptive controller.

A first data evaluation showed that the controller was able to reduce the vibrations drasticly at steady-state as well as at time-variing flight-conditions. A surprising result however was the fact that all dynamic rotor components could be influenced simultanously by only one HHC input-signal. Furthermore a nearly constant phase shift of the rotor transfer function was ascertained within the whole flight envelope.

In the paper the above mentioned rotor characteristic will de demonstrated by wind tunnel data and possible reasons will be specified. These theoretical statements will be supported by simulation results which were attained with different rotor and downwash models thus showing the influence of the various aerodynamic and aeroelastic phenomena on the discovered rotor behaviour. Finally a controller which works with a constant feedback phase shift will be presented and compared with a full adaptive one.

1. Introduction

Although it is well known that the flight envelope of a helicopter can be extended by active control of the main rotor this technology is still not standard nowadays. One reason may be the high amount of additional costs which arise by integrating active rotor control in an already existing helicopter concept thus making it to expensive and therefore not attractive for the user.

Nevertheless lower costs can be achieved if active control is already considered during the design phase of a helicopter because in this case better conditions for the realization are reachable. Last but not least due to the manifold possibilities, represented for example by the vibration reduction or the gust alleviation, active rotor control will be standard in future helicopters.

For that reason the DLR Institute for Flight Mechanics decided to perform investigations on the field of active rotor control aiming in a first step upon the reduction of the relative high helicopter vibration level. After having shown analytically that a considerable reduction of the dynamic rotor forces and -moments by Higher Harmonic Control is possible at a hingeless rotor [1] a wind tunnel demonstration was performed in order to allow a verification of these theoretical results [2]. Whereas in a first step the higher harmonic control parameters were adjusted manually by the test engineer in a second step a digital controller was implemented which determined the higher harmonic blade pitch angles leading to a minimum of vibrations.

Due to the time variing state of the rotor this controller was choosen as an adaptive one thus identifying the transfer function of the plant, in this case represented by the rotor, in every cycle before the optimal amplitudes and phase shifts of the 3-, 4- and 5/rev blade pitch angle were determined. This proceeding lead to a stable controller which was able to reduce the vibrations within the whole flight envelope [3]. Based upon these results an improved controller was developped which works with a constant phase shift of the plant's transfer function and only identifies the respective gain in every cycle. This kind of controller possesses a better behaviour especially at very fast maneuvers as can be seen from the following chapters.

2. Test Equipment

2.1 Rotor Test Rig

The tests were conducted in the German-Dutch Wind Tunnel (DNW) with the DLR rotor test rig (ROTEST, Figure 1) whose major part was formed by the rotor. It was choosen as a Mach-scaled modell of the MBB BO105-main rotor in order to make the wind tunnel results transmittable to a real helicopter.

As can be seen from Figure 1 the test rig was equiped with a high number of sensors allowing a comprehensive observation of the system state.

Strain gages, for example, had been applied to the rotor making it possible to determine the rotor reaction in dependance of HHC inputs by surveying the flapping, lagging and torsional motion of the blades.

The vibrations in the fixed system could be measured with the rotor balance which incorporated seven sensor systems consisting of a strain gage part and a pieco electrical part. Whereas the strain gage part allowed to measure the static forces, the pieco electrical part made it possible to determine the dynamic forces, both with a high accuracy.

The accelerations in the fixed system could be measured by three additional accelerometers which were implemented close to the rotor. This sensors can also be applied to a real helicopter allowing to generate the wind tunnel results comparable with flight test data.

2.2 HHC Computer System

The higher harmonic control signals were generated by a digital computer system [4] which made it possible to adjust the HHC control parameters manually by the test engineer as well as automatically by a controller (fig. 2). This controller consisted of a Kalman filter and a minimum variance controller and aimed upon the minimization of the quadratic quality criterion

$$GF = \underline{z}^T((k+1)T_s) \cdot \underline{W}_z \cdot \underline{z}((k+1)T_s) + \underline{\Theta}^T((k+1)T_s) \cdot \underline{W}_\Theta \cdot \underline{\Theta}((k+1)T_s)$$

with

$\underline{z}(kT_s)$ a vector including the cosine and sine components of the 4/rev part of the vibrations in the fixed system,

$\underline{\Theta}(kT_s)$ a vector including the cosine and sine components of the higher harmonic control signals in the rotating system,

k the sample index,

T_s the sample period

and

$\underline{W}_z, \underline{W}_\Theta$ weighting matrices.

During the wind tunnel tests the weighting matrix $\underline{W}_\Theta$ was set to $\underline{0}$ in order to avoid penalizing of the higher harmonic control inputs and to achieve a good behaviour at variing flight conditions.

3. Test Results

3.1 Open-loop Tests

During the first tests of the wind tunnel campagne the higher harmonic control parameters were adjusted manually by the test engineer in order to allow a systematically investigation of the rotor reaction in dependance of HHC inputs as well as an offline-identification of the rotor transfer function $\underline{T}$. The proceeding choosen for the accomplishment of these tasks was to select an arbitrary amplitude of the 3-, 4- or 5/rev blade pitch angle and to vary the respective phase shift stepwise from 0° to 360°. Holding constant the value which leads to the best vibration reduction and variing the corresponding amplitude resulted in the optimal control parameters for the 3-, 4- and 5/rev blade pitch angle. For a combination of two or three HHC-signals the optimal amplitude and phase shift value of one higher harmonic blade pitch angle was fixed before the remaining free control parameters were varied as described above.

Fig. 3 shows the surprising result and makes clear that a 3/rev blade pitch angle yielded in nearly the same vibration reduction as could be achieved with a combination of two or three higher harmonic control signals.

The reason for this behaviour is illustrated in fig. 4 which makes clear that the 3/rev blade flapping moment is dominant within the whole range of speed whereas the 4- and the 5/rev part nearly vanishes and therefore is neglectible. Obviously in forward flight the blade forcing terms act in a way that leads to a strong excitation of the second flapping mode having an eigenfrequency ratio of 2.7.

However these blade forcing terms seem to originate from different aerodynamic effects as is indicated by the significant minimum of the phase-shift corresponding to the 3/rev blade flapping moment (fig. 5). Whereas the non-uniform downwash distribution within the rotor disk is assumed of being responsible for the vibrations in the fixed system at low velocities, its influence obviously decreases with speed whereas other aerodynamic phenomena, for example Mach-effects etc., become more and more important.

Nevertheless the 3/rev blade pitch angle obviously succeeds in suppressing the excitation of the second flapping mode, provided that its amplitude and phase shift is varied with speed as shown in fig. 6 and fig. 7. In opposition to the expectations this proceeding does not only lead to a simultanous influencing but furthermore to a simultanous reduction of all dynamic rotor forces and moments as is shown in fig. 8 and fig. 9 exemplarily for a velocity of 50 m/s.

Another important result derivable from the wind tunnel data concerns the rotor transfer function which is represented by the so called $\underline{T}$ -matrix. It is of the form

$$\underline{T} = \begin{bmatrix} \underline{T}_{1,3} & \underline{T}_{1,4} & \underline{T}_{1,5} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \underline{T}_{5,3} & \underline{T}_{5,4} & \underline{T}_{5,5} \end{bmatrix}$$

with

$\underline{T}_{i,j}$ the transfer function of the i-th rotor component and the j-th higher harmonic control signal

and is defined by the equation

$$\Delta\underline{z} = \underline{T} \cdot \Delta\underline{\Theta}$$

with

$\Delta\underline{z}$ the vector of vibration change

and

$\Delta\underline{\Theta}$ the vector of the higher harmonic input change.

This T-matrix can be ascertained definitely if the HHC-parameters are adjusted in a way that the vector $\Delta\underline{\Theta}$ vanishes except of one of its components. The corresponding column of the T-matrix can then be determined by measuring the output vector $\Delta\underline{z}$ and relating its components to the remaining element of the the control vector $\Delta\underline{\Theta}$. This proceeding yields a 2x2-submatrix $\underline{T}_{i,j}$ of the form

$$\underline{T}_{i,j} = \begin{bmatrix} T_{i,j_c} & -T_{i,j_s} \\ T_{i,j_s} & T_{i,j_c} \end{bmatrix}$$

with

T_{ij_c} the real-

and

T_{ij_s} the imaginary part of the transfer function

and can be represented in an amplitude/phase shift notation too as is done in fig. 10 and fig. 11. They show the result of the above mentioned calculation if applied to the wind tunnel data and indicate that the amplitudes of the transfer function vary in a wide range whereas the corresponding phase shifts remain nearly constant within the whole range of speed. This behaviour allows the realization of a partial adaptive controller which only determines the gains of the rotor transfer function while the phase shifts are kept constant.

3.2 Closed-loop Tests

In order to proof wether the controller is able to reduce the vibrations in principle, the first closed-loop tests were conducted at steady flight conditions. One result is pointed out in fig. 12 which makes clear that the 3/rev controller approached directly the amplitude and the phase shift which was found out to be optimal during the open-loop tests. As can be seen from fig. 13 this behaviour yielded in a simultanous reduction of all dynamic rotor forces and moments, a result which supports the observation of the open-loop tests.

The HHC-parameters ascertained by the controller which works with a 3- and 4/rev blade-pitch-angle are shown in fig. 14. It makes clear that, after enabling the HHC computer system, both control amplitudes at first increased in a similar way. Then the good efficiency of the 3/rev blade-pitch-angle obviously was noticed by the controller thus reducing the 4/rev amplitude again and adjusting a 3/rev blade pitch angle close to the 3/rev only HHC amplitude.

Fig. 15 shows the correponding tendency of the quality criterion and makes clear that, compared with the result of the 3/rev controller, a slightly improved vibration reduction (about 9%) could be attained. A disadvantage however was the extension of the controller response time by 100% which of course resulted from the higher amount of free parameters to be determined.

In the case of the controller choosen here these parameters are not only represented by the HHC amplitudes and phase shifts but in addition by the elements of the T-matrix to be determined in every cycle. The quantity of the latter ones can be reduced by using a partial adaptive controller which, as already mentioned, works with a constant feedback phase shift and only estimates the corresponding gain. Therefore it is assumed to have a short response time, especially if working with a 3/rev blade pitch angle only, a statement which will be proofed by simulation results in chapter 4.2.3.

4. Theoretical Investigation and Simulation Results

4.1 Simulation Model

In order to investigate the reasons for the good effectiveness of the 3/rev blade pitch angle and to test the behaviour of the partial adaptive controller a simulation program was used which in detail is presented in [5]. As can be seen from fig. 16, this program describes the blade motions by up to three flapping, two lagging and one torsional mode being the result of a Finite Element calculation. The number of modes taken into account for the simulation can be selected interactively by the user thus giving a possibility to adapt the computing time to the required accuracy.

Besides the number of blade modes the kind of rotor downwash modelling can be choosen too. One possibility is the well-known Mangler-Squire method [6] which yields a non-uniform distribution of the induced velocitiy within the rotor disk and therefore leads to results which are more realistic than those attainable with a constant or trapezoidal downwash model.

A second possibility which can be choosen is a method following Beddoes [7] which describes the rotor downwash by individual vortices with prescibed distorted geometry. Compared with the Mangler model this proceeding leads to additional peaks of the induced velocity especially in the front part of the rotor disc and therefore is well-suited to represent specific effects like blade vortex interaction for example.

4.2 Simulation Results

4.2.1 Reference Data

In order to allow an assessment of the HHC efficiency, reference data are required which describe the dynamic characteristic of the rotor. For that reason the simulation program was operated in a first step without higher harmonic control inputs at different velocities taking into account all above mentioned blade modes. The flight conditions were choosen to be the same as adjusted in the wind tunnel, that means, scaled thrust and vanishing rotor moments.

The result is shown in fig. 17 and fig. 18 which make clear that, independant of the downwash model, the 3- and 4/rev part of the first and second flapping mode form the major part of the higher harmonic blade motion. This observation supports the above mentioned assumption, that the second flapping mode which has an eigenfrequency ratio of about 2.7 is strongly excited in forward flight. The first flapping mode of course is excited too but due to its eigenfrequency ratio of about 1.2 the resulting amplitudes are smaller. Nevertheless both modes should be taken into account for simulations concerning higher harmonic control in order to attain realistic results.

The correponding vibrations in the fixed system, represented by the quality criterion

$$GF = F_x^2 + F_y^2 + F_z^2 + M_x^2 + M_y^2$$

with

F_x, F_y, F_z, M_x, M_y the 4/rev part of the rotor forces and moments

are shown in fig. 19. It makes clear that both downwash methods yield the same helicopter specific tendency but the Beddoes model leads to a better approximation of the wind tunnel data and therefore was used for simulations in conjunction with higher harmonic control.

4.2.2 Rotor Reaction on Higher Harmonic Control Inputs

After having shown that the simulation program is able to represent the vibratory behaviour of the rotor in principle, calculations in conjunction with higher harmonic control were performed. They aimed upon an explanation of the rotor behaviour discovered in the wind tunnel and were based on former investigations performed with the Mangler downwash model [8]. These investigations resulted in the statement that a good approximation of the optimal higher harmonic control parameters can be achieved if two flapping and one torsional mode is taken into account for the simulations. Nevertheless this combination only leads to a vibration reduction of maximal 30% and especially does not represent the good efficiency of the 3/rev blade pitch angle.

In order to eliminate these disadvantages, simulations with the downwash model following Beddoes and an additional flapping mode were performed. As can be seen from fig. 20 they resulted in a vibration reduction of about 75% if a combination of a 3-, 4- and 5/rev blade pitch angle was superposed to the conventional control signals. However the observation ascertained in the wind tunnel, that an additional 4- and 5/rev HHC signal only leads to a marginale improvement of the 3/rev result could not be confirmed within the scope of these simulations.

For that reason the above mentioned rotor model was extended by two additional lagging modes and then was operated under the same conditions as done before. Fig. 21 shows the result and makes clear that a downwash model following Beddoes combined with a description of the rotor behaviour by three flapping, two lagging and one torsional mode leads to a satisfactory vibration reduction independant of the HHC input combination. In addition it approximates the efficiency of the 3/rev blade pitch angle in a sufficient way as can be derived from the vibration reduction achieved with a 3- and 4/rev- as well as with a 3-, 4- and 5/rev HHC input combination. Both yield an improvement of the 3/rev result by about 8.7% and 13.1% respectively which is similar to this one measured in the wind tunnel.

The reason for this behaviour is illustrated in fig. 22 and fig. 23 which show the dependance of the first and second flapping mode on the HHC phase-shift. They make clear that especially the 3/rev and the 4/rev part of these modes which, as already mentioned above, form the major part of the higher harmonic blade motion can already be influenced in a wide range by a 3/rev blade pitch angle (fig. 22). An additional 4/rev higher harmonic control signal however only leads to a little variation (fig. 23), a result which correlates clearly with the achievable vibration reduction represented in fig. 21.

4.2.3 Behaviour of the Partial Adaptive Controller

Besides the investigation of the good 3/rev efficiency the second aim of the simulations was to test the behaviour of the partial adaptive controller. As already mentioned above this kind of controller only identifies the gain of the rotor transfer function at every cycle whereas the respective phase shift is kept constant.

In order to find the optimal value for this phase-shift a new quality criterion was introduced being defined by the equation

$$J = \sum_{i} e_i^2$$

with

e_i the difference of the choosen and the real phase shift (see fig. 24).

The minimum of this quality criterion indicates the optimal phase shift value of the rotor transfer function and therefore was determined by systematically variing the free parameter from 0° to 360°. The resulting tendency of the quality criterion is shown in fig. 25 which makes clear that in the example choosen here the phase shift becomes optimal at 96° .

The behaviour of the controller which works with this constant value and only identifies the corresponding amplitude is shown in fig. 26. It makes clear that the vibration level achievable with the full-adaptive controller can not be attained in the case of a constant phase shift but the response time is suppressed by about 25%. This result of course is a matter of the smaller amount of free parameters to be determined which on the one hand leads to a reduced computation time but on the other hand forces the partial adaptive controller in opposition to the full-adaptive one to approach the optimal parameters directly. It therefore is able to keep the vibrations small even at fast flight maneuvers, a property which is advantagous especially in the case of a hingeless rotor.

5. Conclusions

Based upon wind tunnel test results it was demonstrated that a 3/rev blade pitch angle is able to reduce all dynamic rotor components simultanously. The reason for this behaviour was investigated within the scope of simulations performed with different rotor and downwash models. Besides these investigations the simulations aimed upon a testing of the partial adaptive controller which only identifies the amplitude of the rotor transfer function at every cycle whereas the corresponding phase shift is kept constant.

Summarizing the results the following statements can be made:

- The 3- and the 4/rev part of the first and second flapping mode form the major reason for the vibrations in the fixed system.
- Both can be influenced by a 3/rev blade pitch angle in a way that leads to a simultanous reduction of all dynamic rotor components.
- The resulting vibration level is similar to this one achievable with a 3-, 4- and 5/rev HHC combination.
- The partial adaptive controller works stable and possesses a shorter response time than the full-adaptive one.

6. References

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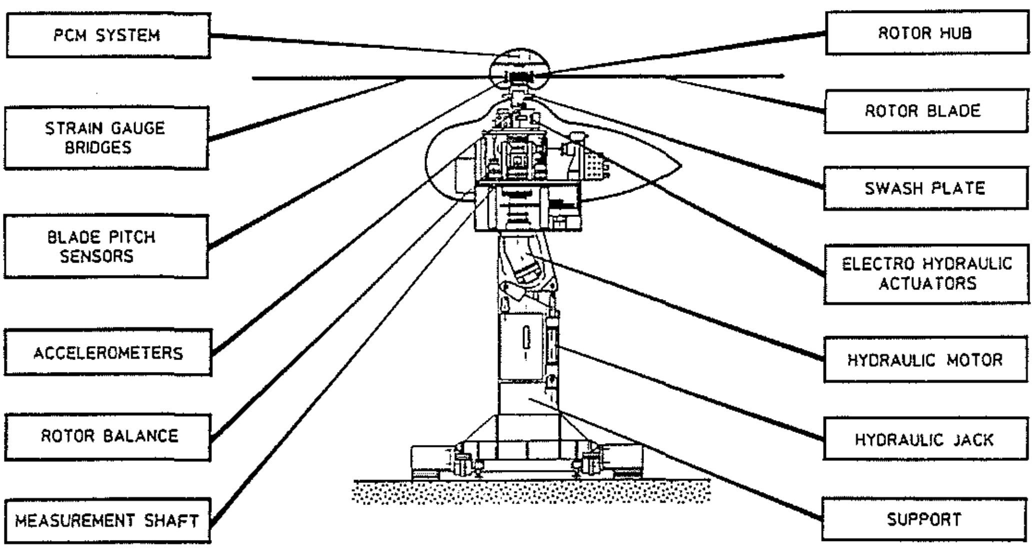

Figure 1. Schematic of the DLR-Rotor Test Stand

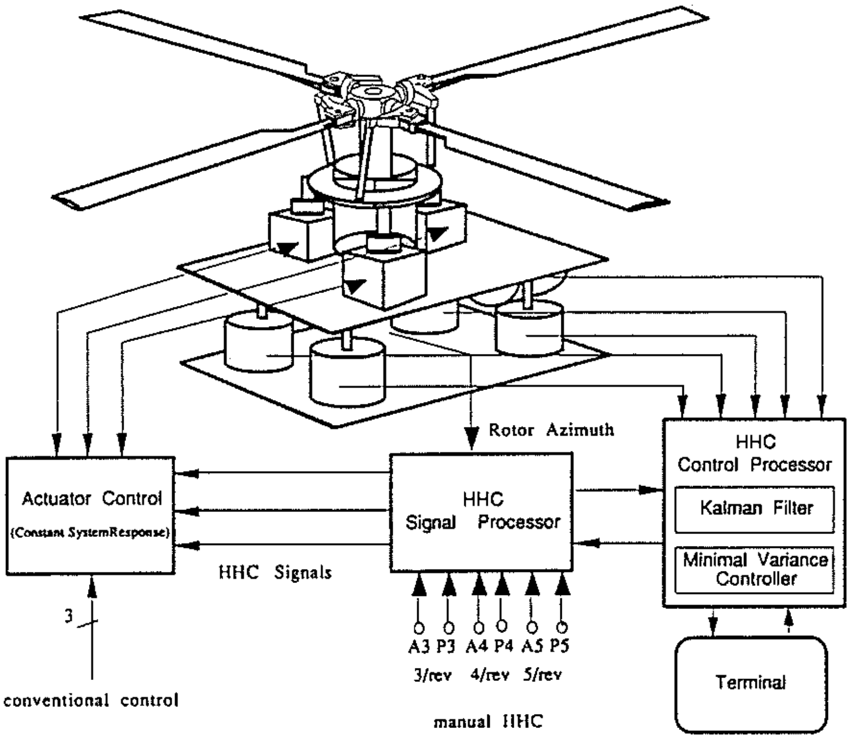

Figure 2. Schematic of the HHC Computer System

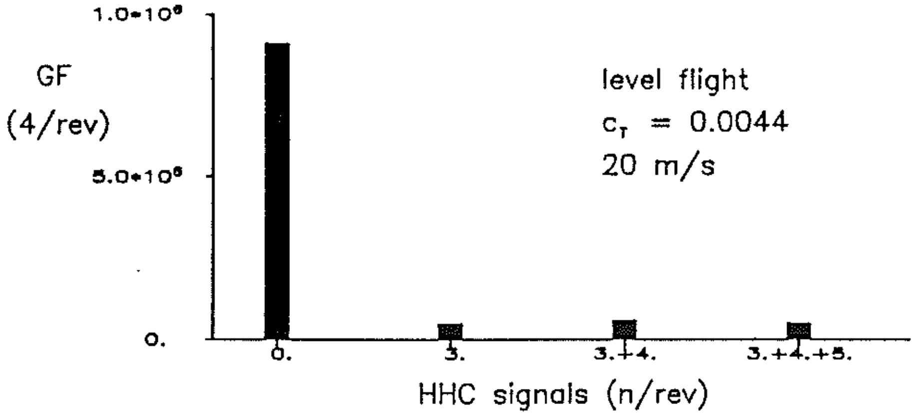

Figure 3. Quality Criterion for Different HHC Input Combinations

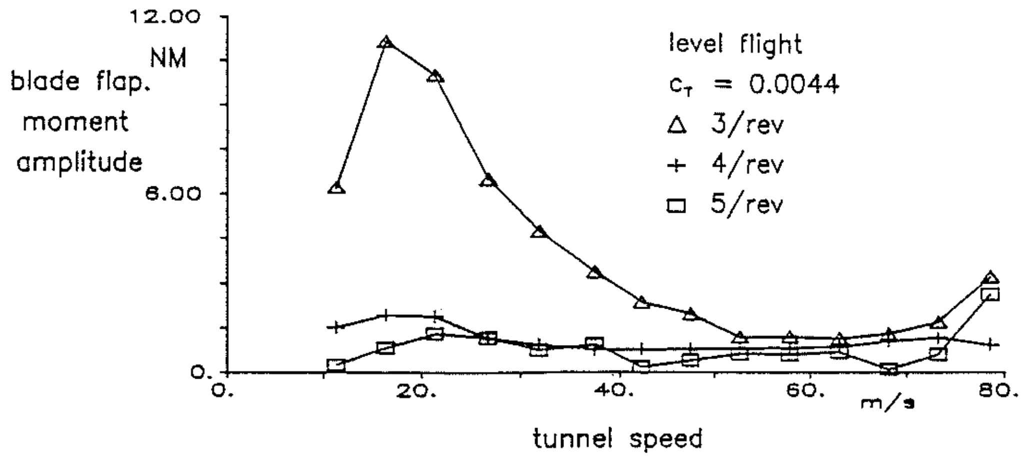

Figure 4. Amplitude of Blade Flapping Moment at r/R=0.15

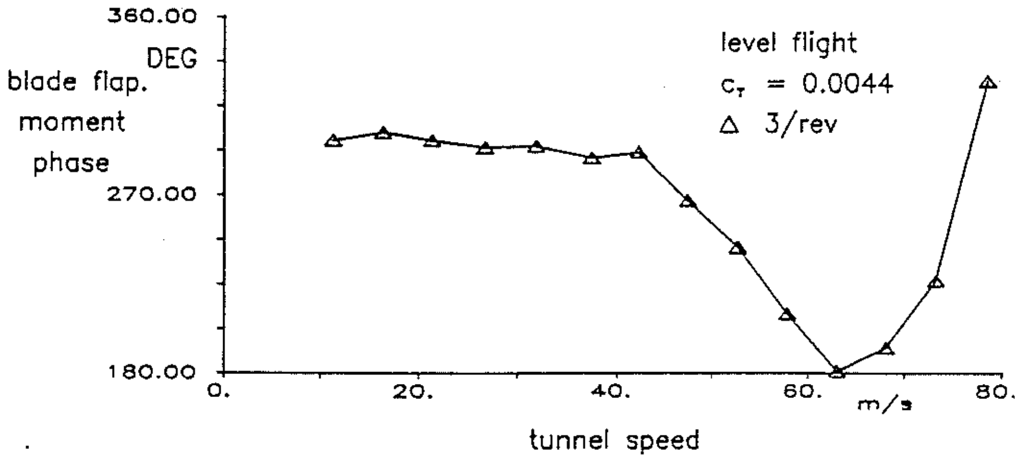

Figure 5. Phase Shift of Blade Flapping Moment at r/R=0.15

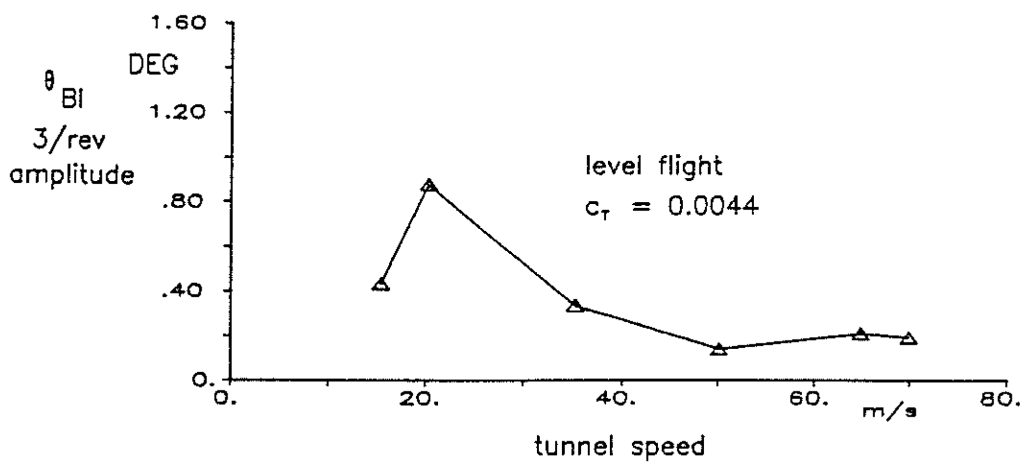

Figure 6. Optimal 3/rev Amplitude

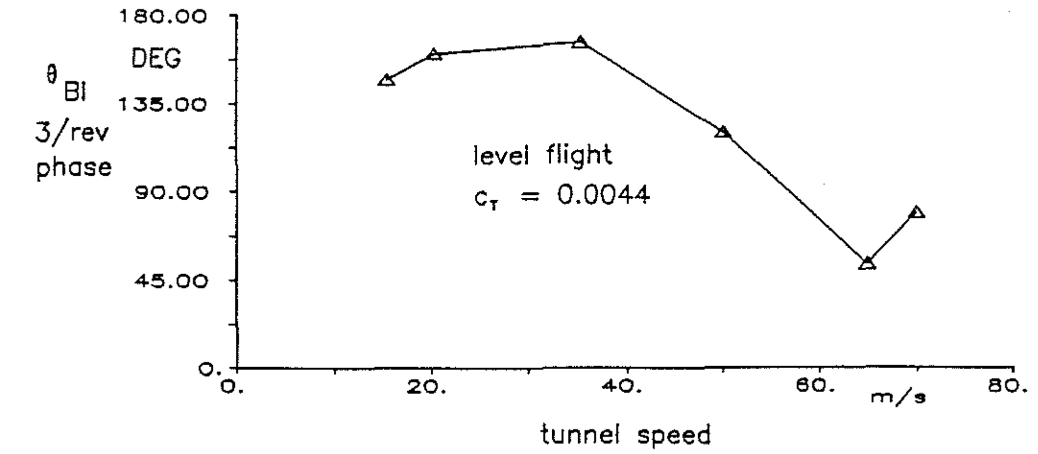

Figure 7. Optimal 3/rev Phase Shift

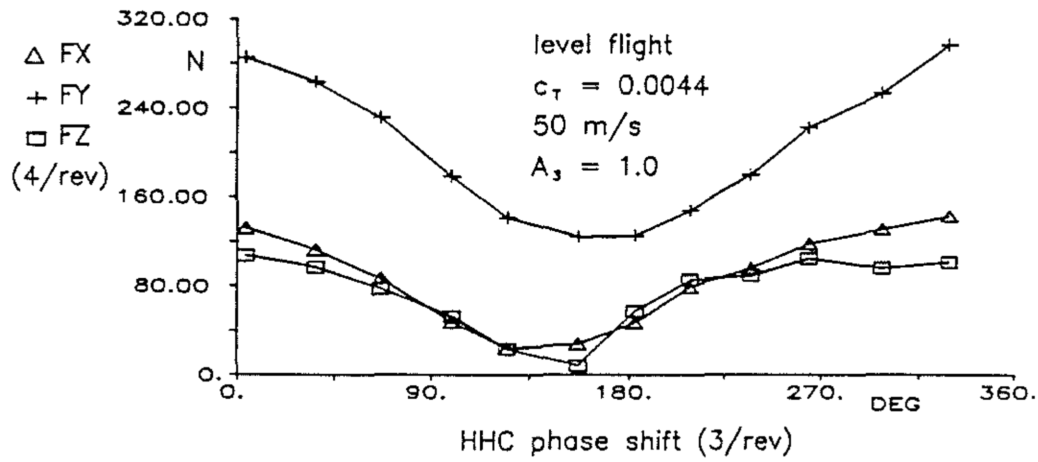

Figure 8. Dependance of Rotor Forces on 3/rev Phase Shift

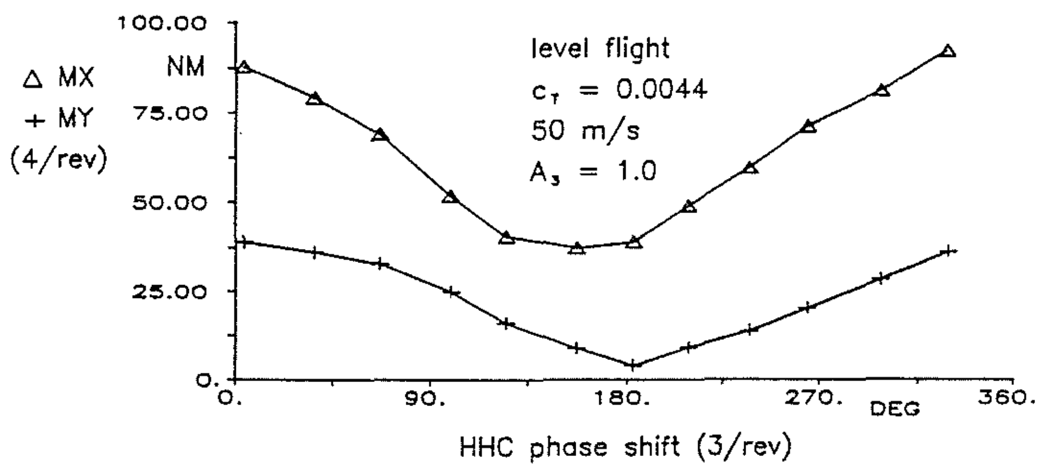

Figure 9. Dependance of Rotor Moments on 3/rev Phase Shift

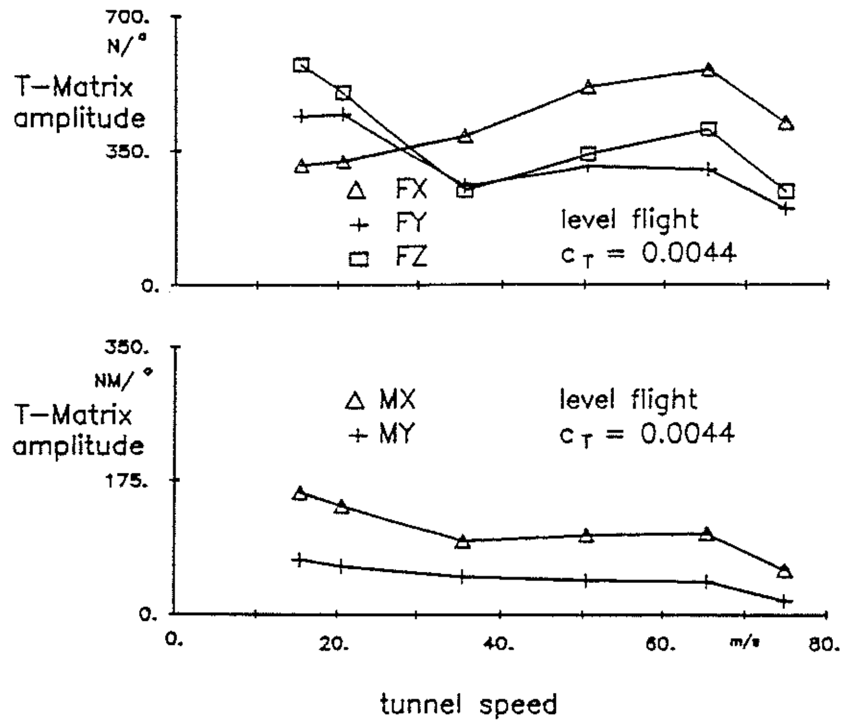

Figure 10. Amplitude of T-Matrix Elements for 3/rev HHC

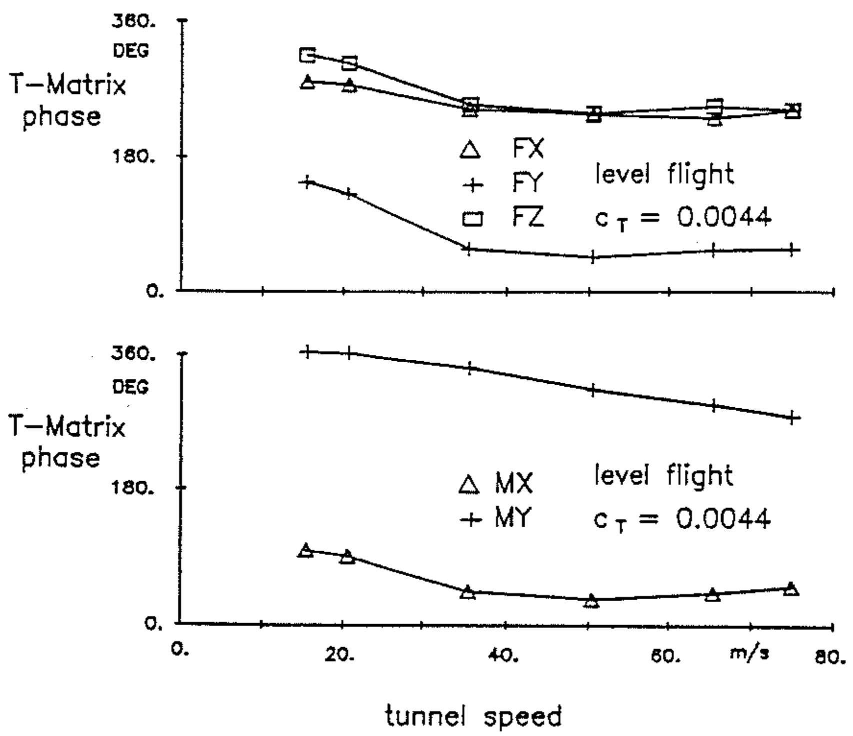

Figure 11. Phase Shift of T-Matrix Elements for 3/rev HHC

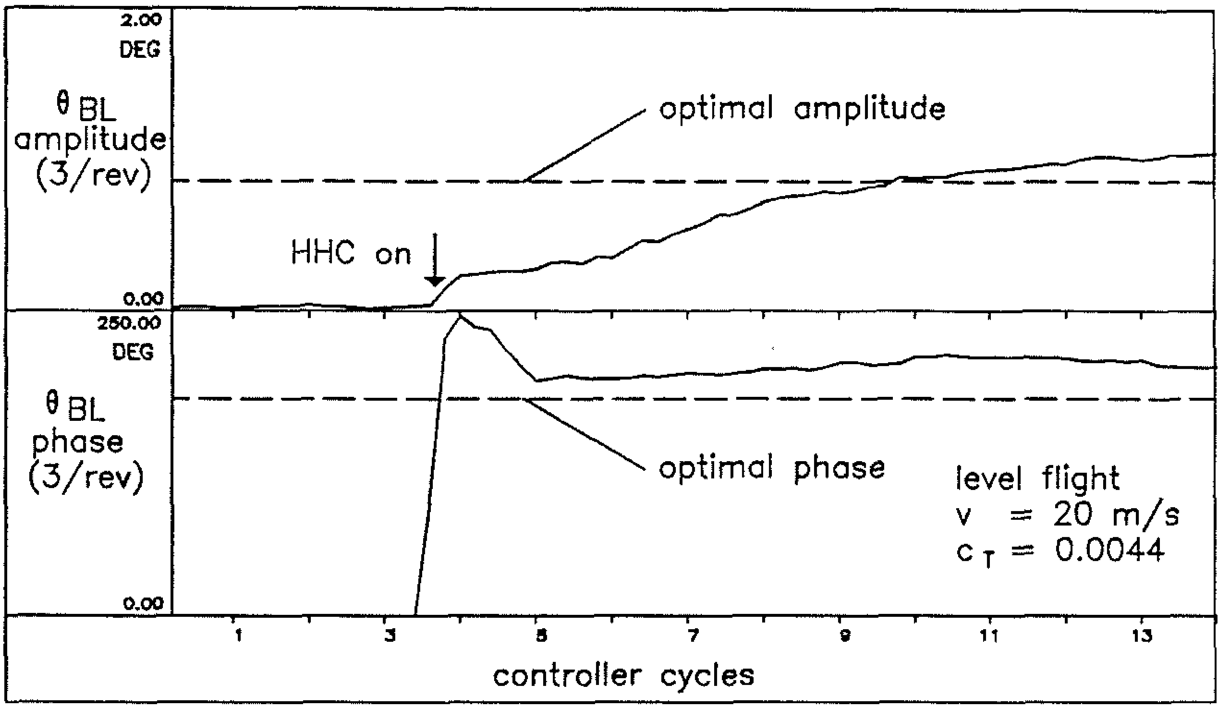

Figure 12. Output of the 3/rev Controller

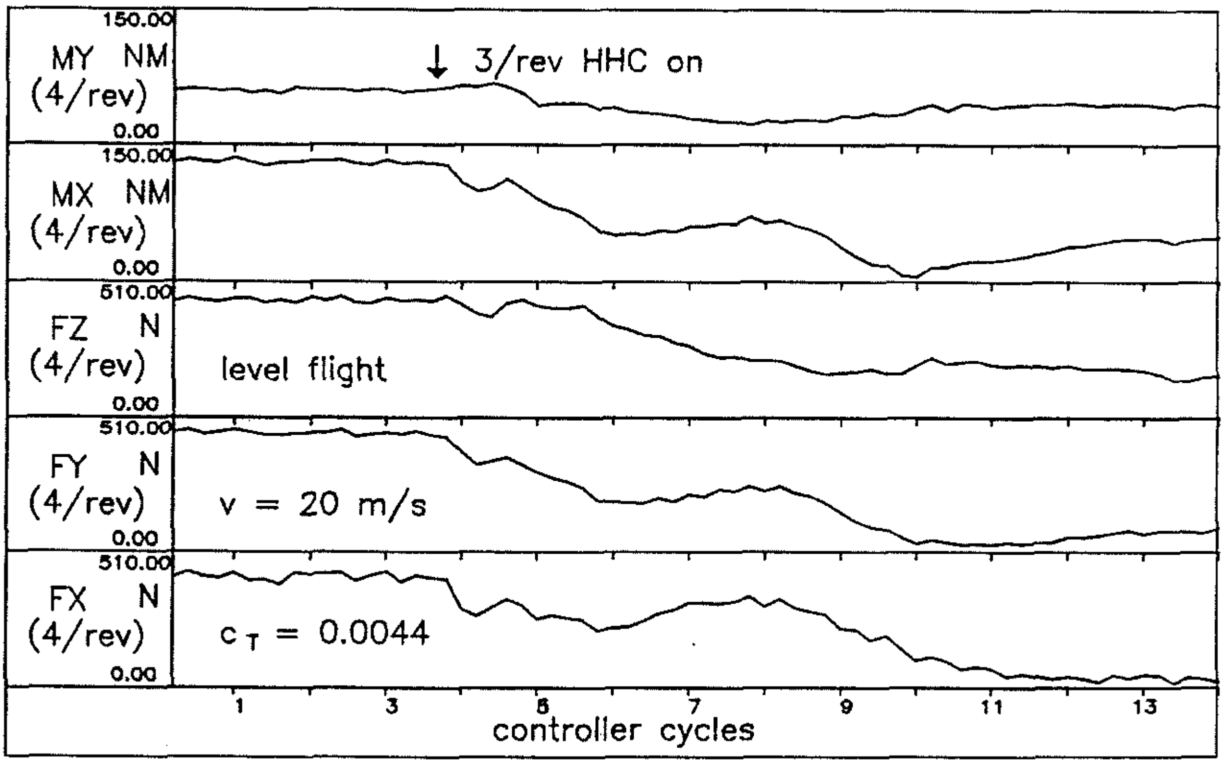

Figure 13. Performance of the 3/rev Controller

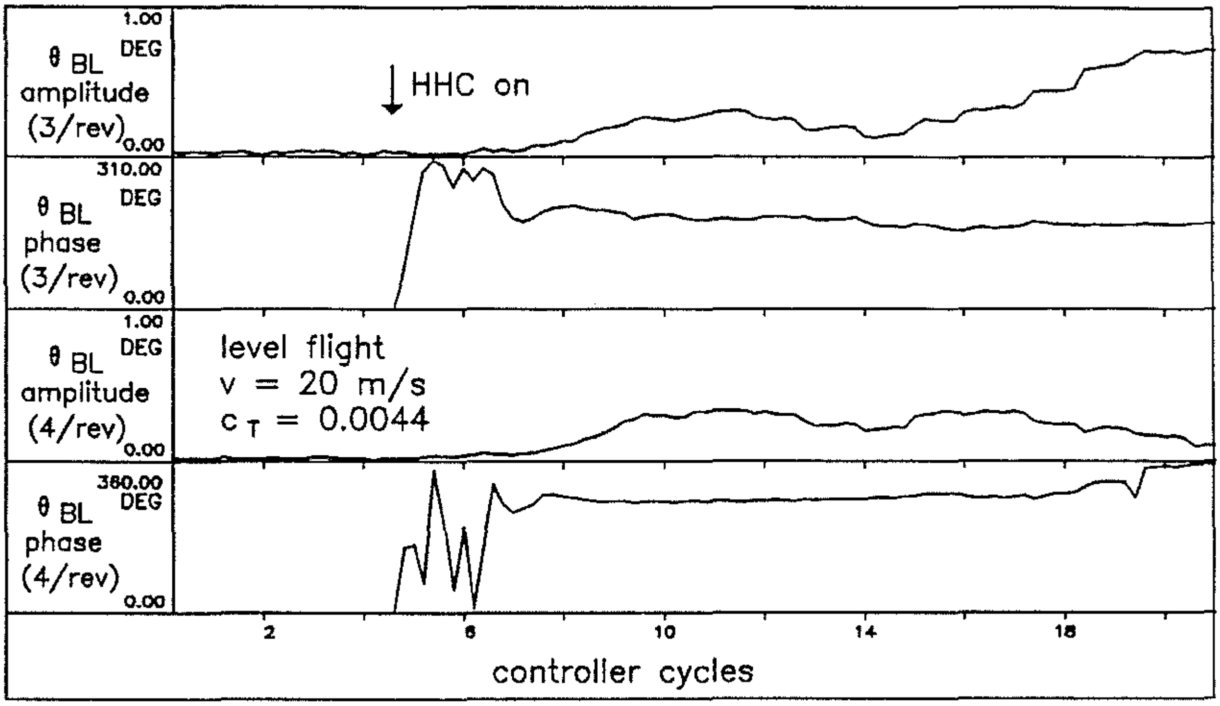

Figure 14. Output of the (3+4)/rev Controller

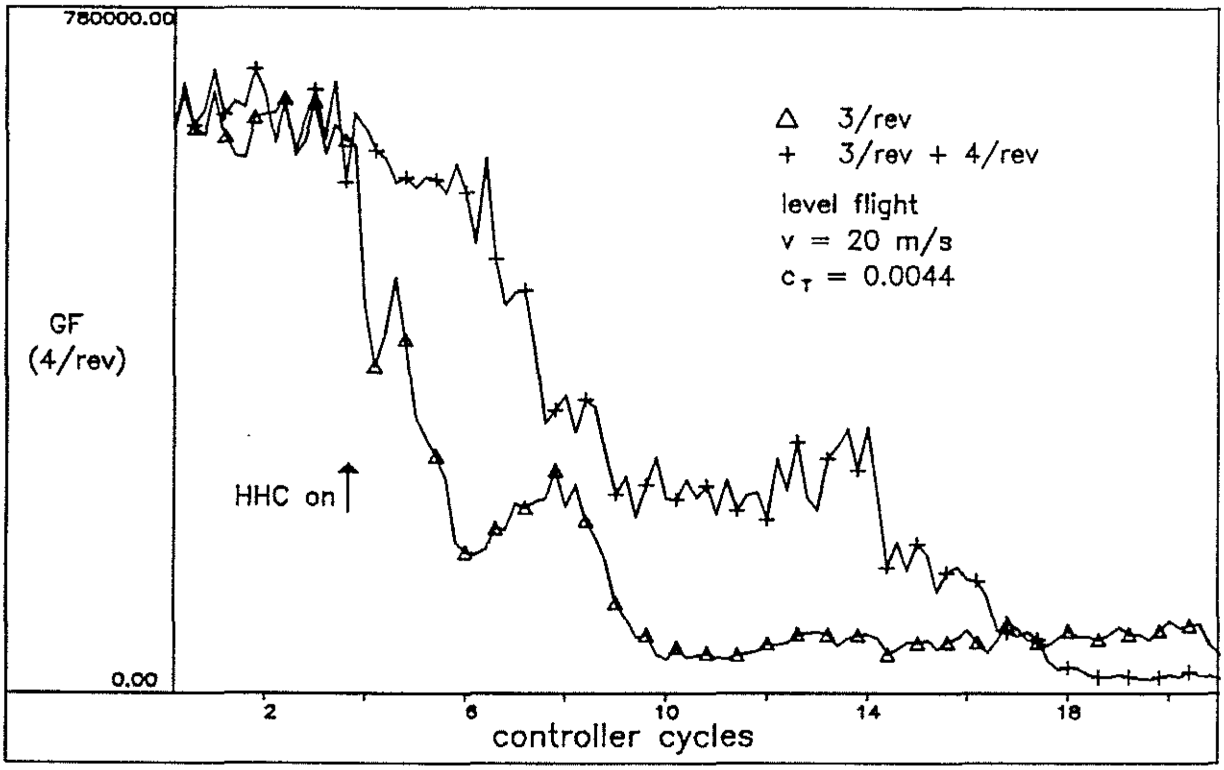

Figure 15. Comparison of Controller Performance

Number of Flapping Modes	up to 3
Number of Lagging Modes	up to 2
Number of Torsional Modes	up to 1
Downwash Model	Mangler / Beddoes

Figure 16. Features of the Simulation Program

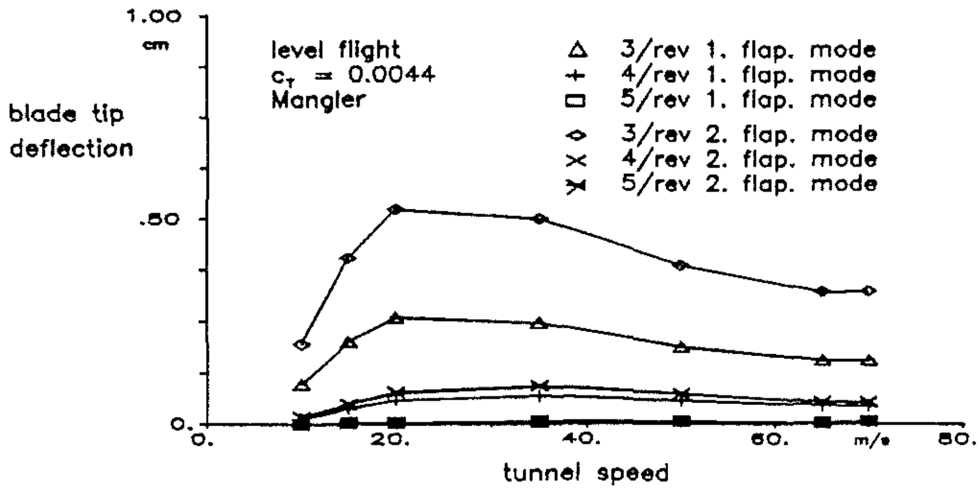

Figure 17. Blade Tip Deflection for Mangler Downwash

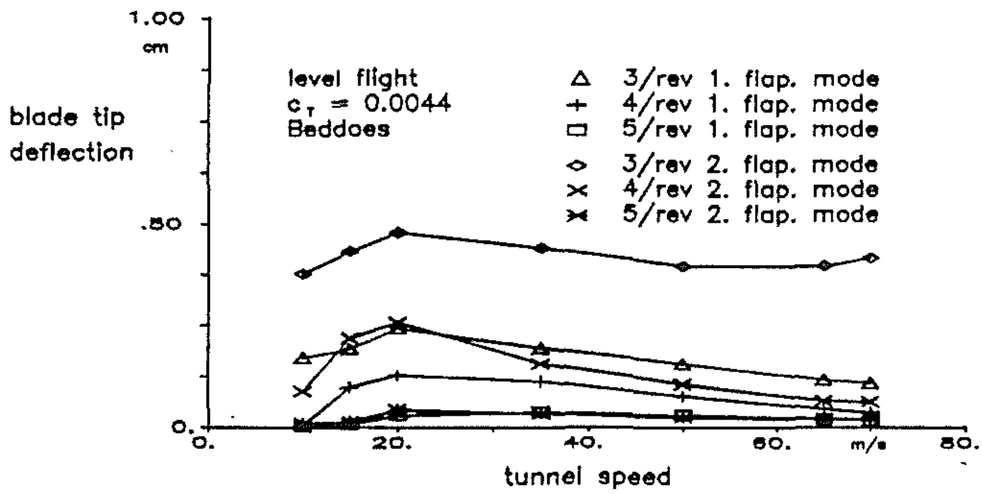

Figure 18. Blade Tip Deflection for Beddoes Downwash

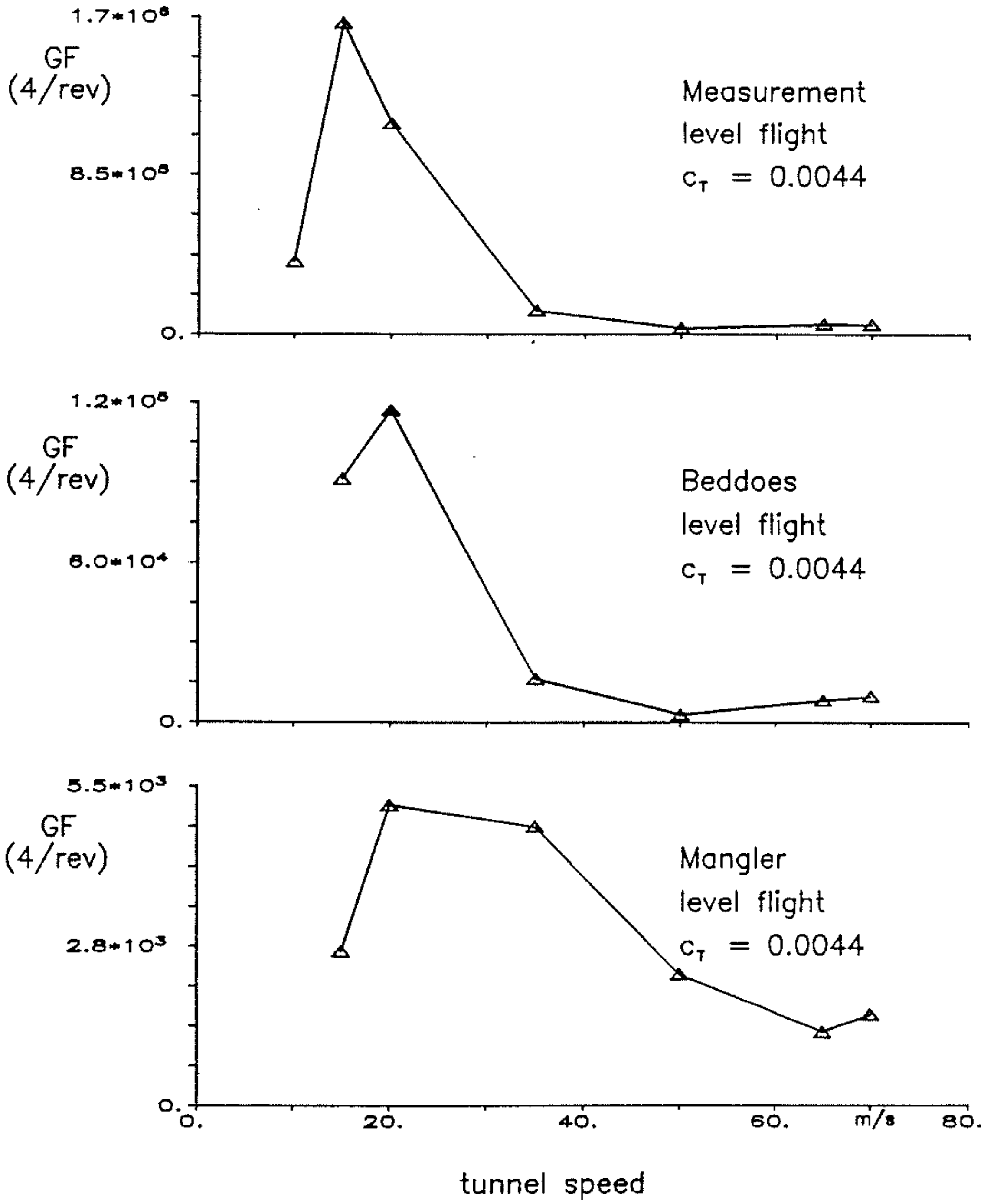

Figure 19. Dependance of Quality Criterion on Velocity

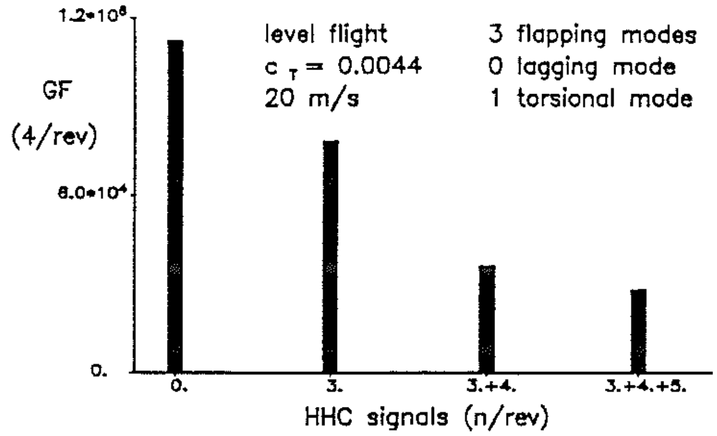

Figure 20. **Quality Criterion for Simulation without Lagging Motion**

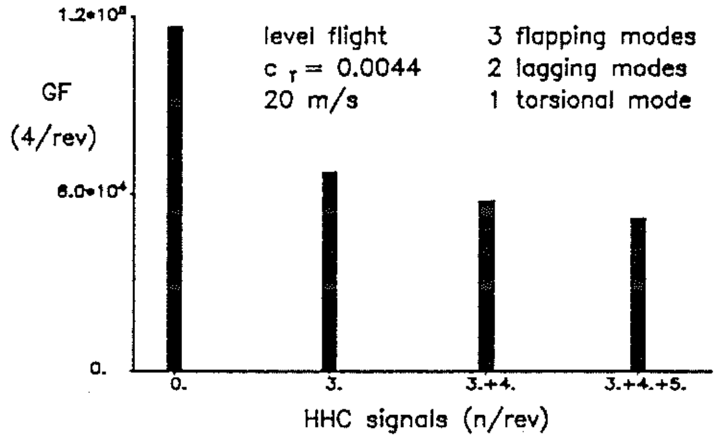

Figure 21. **Quality Criterion for Simulation with Lagging Motion**

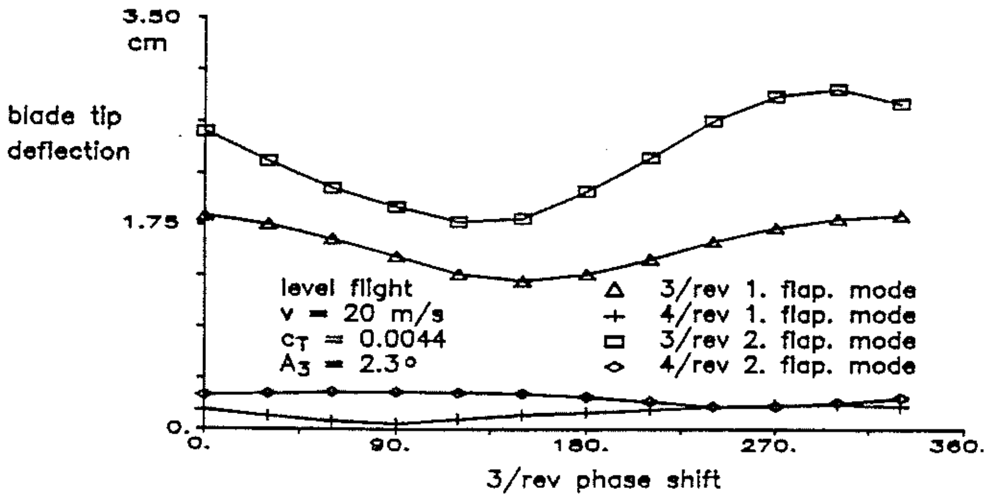

Figure 22. **Dependance of Blade Tip Deflection on 3/rev Phase Shift**

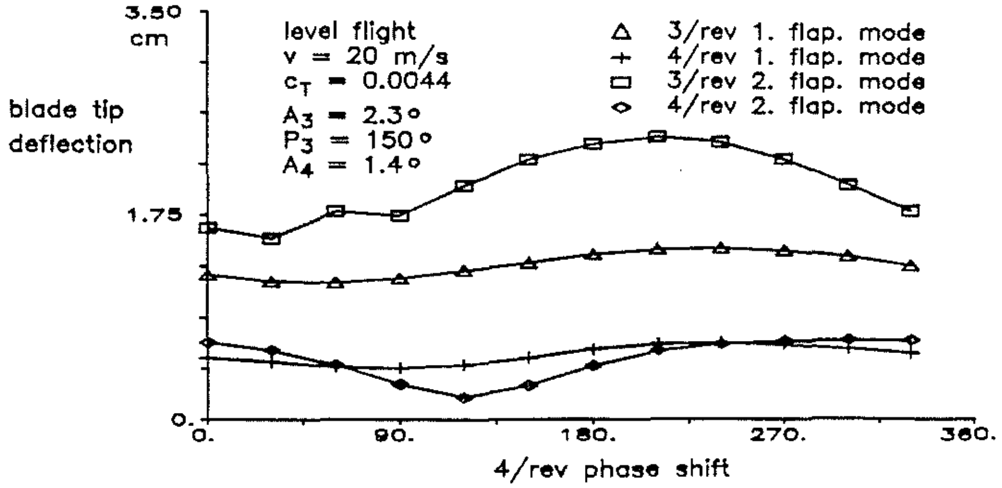

Figure 23. Dependance of Blade Tip Deflection on 4/rev Phase Shift

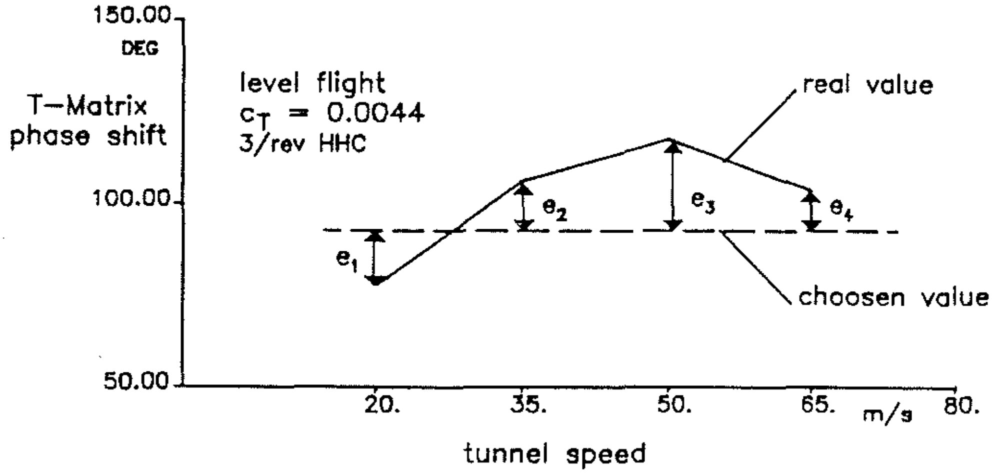

Figure 24. Ascertainment of optimal T-Matrix Phase Shift

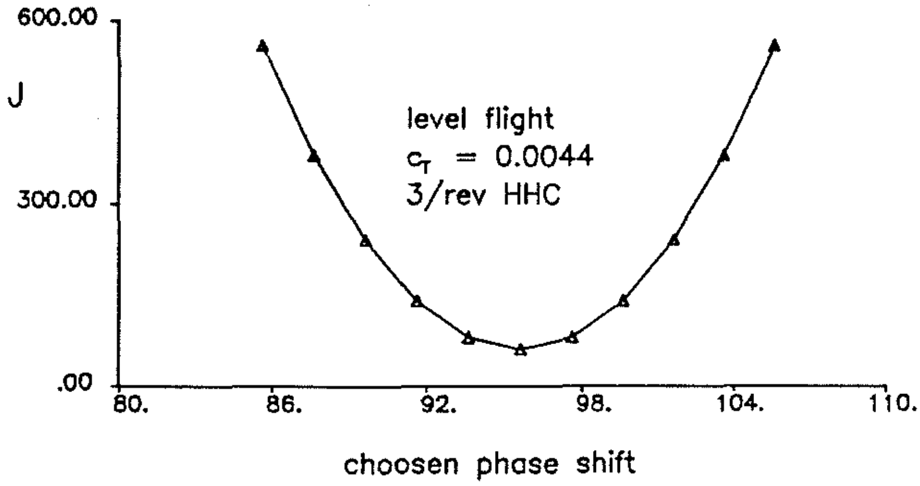

Figure 25. Dependance of New Quality Criterion on Choosen Phase Shift

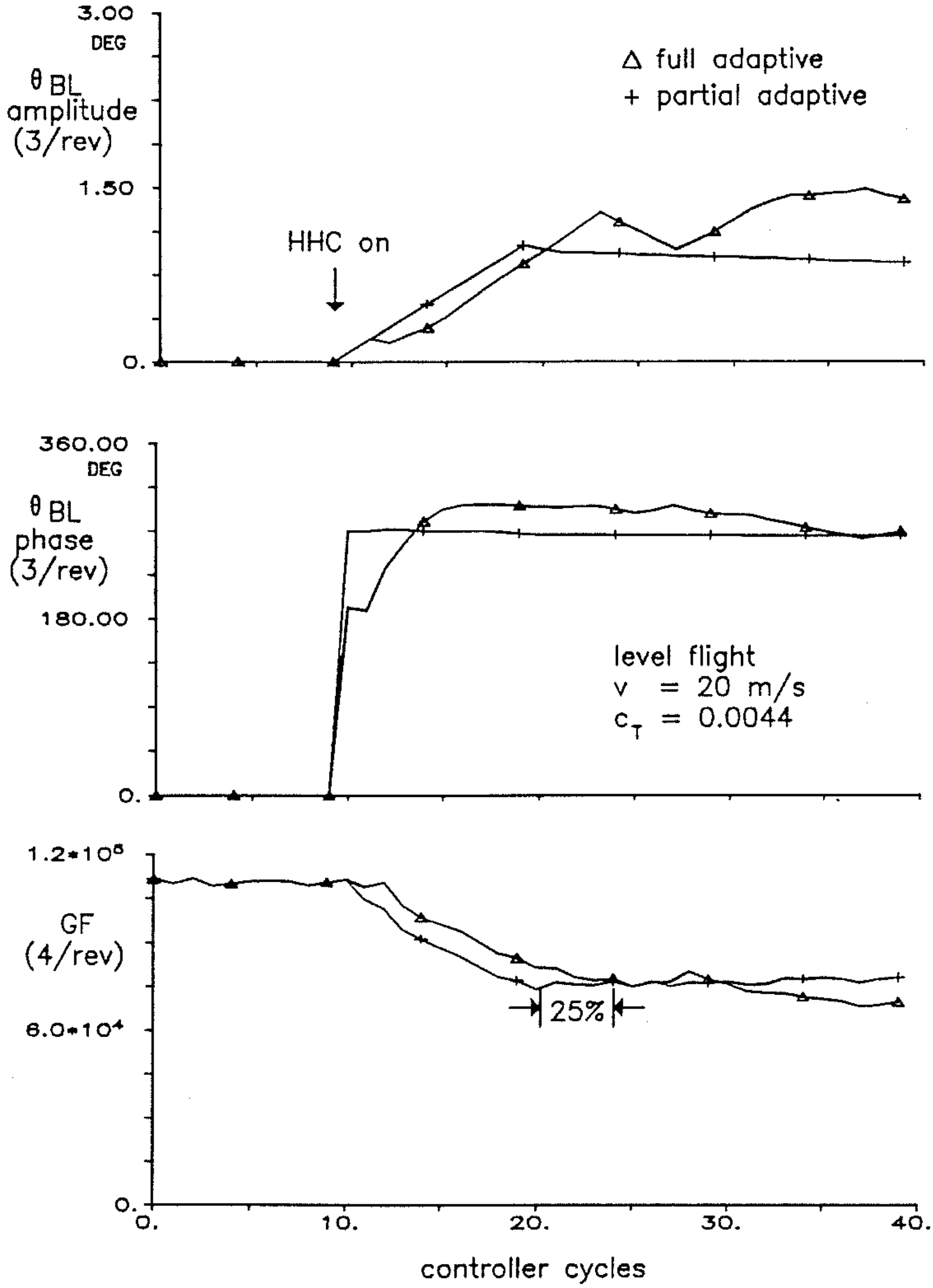

Figure 26. Comparison of Partial and Full Adaptive Controller