HIGHER HARMONICS CONTROL OF HELICOPTER ROTOR WITH ELASTIC BLADES

V.A. Ivchin
MIL Moscow Helicopter plant, JSC
Russia

I.O. Averyanov
“MATI” - Russian State Technological University
Russia

For many years, designers of helicopters are interested in the application of control for harmonics higher than the 1st for rotors. Classic swash allows control of only the 1st harmonic while higher harmonics of blades pitch change allows us to get advantage in performance characteristics and reduce loads in helicopter control system and significantly reduce vibrations in fuselage. This paper is the continuation of the program launched by Mil Design Bureu (MDB) on the development of rotor control system for high harmonics to reduce helicopter vibration level. The goal is to investigate the possibility of multicyclic control system design for Mi-8 helicopter. It is known that rotor blade bending elasticity in the plane of thrust and rotation can have an impact on the lows of high harmonics control. To evaluate these lows we have performed identical researches for elastic rotor blades. These researches have been performed on the basis of forth integration method of elastic rotor blade deformations equations, developed by the authors of this paper. Here we show the results of the researches and its comparison with the data for elastic blades from the previous phases.

Introduction

For many years, designers of helicopters are interested in the application of control for harmonics higher than 1st for rotors. Classic swash allows control of only the 1st harmonic while higher harmonics of blades pitch change allows us to get advantage in performance characteristics and reduce loads in helicopter control system and also significantly reduce vibrations in fuselage.

This paper is the continuation of the program launched by Mil Design Bureu (MDB) on the development of rotor control system for high harmonics to reduce helicopter vibration level [1, 2, 3, 4]. The main goal is to investigate the possibility of multicyclic control system design for Mi-8 helicopter.

Earlier we considered technical possibilities of high frequency signal application in helicopter rotor blade cyclic pitch with the use of the drives on the basis of modern piezoceramic materials in different ways: by way of controlled blade flaps or installation of “angle arms” in pitch links (IBC concept) or by way of installation of “angle arms” between hydraulic actuator and swash (HHC concept).

Investigation of multicyclic Mi-8 rotor control according to the IBS concept was made with the use of MDB flight simulator with comprehensive mathematical model of the rotor with blades elastic in planes of bending and torsion and helicopter dynamics. This model was used to determine high frequency response of hub forces and moments to the multicyclic input signals.

The influence on the 4th, the 5th and the 6th multicyclic harmonics on the dominating 5th content of hub shears and moments was evaluated. Multicyclic amplitudes were imposed in the form of equivalent pitch angle of each rotor blade.

The obtained data are pertinent to evaluate the applicability of the rotor/helicopter model for multicyclic control investigations, and evaluate by the first approximation the influence of various input harmonics on hub forces and moments content.

It is known, however, that rotor blade bending elasticity in the plane of thrust and rotation can have an impact on the lows of high harmonics control. To evaluate the lows we have performed identical researches for elastic rotor blades.

The researches have been performed on the basis of forth integration method of elastic rotor blade deformations equations, developed by the authors of the present paper [5, 6, 7]. The equations are based on the theory by A.Y. Liss [8].

This paper presents the researches of high frequency harmonics control application for Mi-8 helicopter for the flight regimes considered in [3,4], considering blades elasticity in planes of bending and torsion. Calculations were made with the characteristics of Mi-8 rotor blade used in MDB. We present the results of the researches and their comparison with the data for elastic blades from the previous phases.

Method of high harmonics control action modeling

We use the same method as in [1-4] for calculations of rotor blade that is assumed elastic in planes of bending and torsion. According to the task of this study the model of helicopter flight control system includes all real kinematical parameters and a model of an autopilot installed on this helicopter. Multicyclic control is entered by insertion in feathering angle of each blade additional quantities with given parameters or with parameters determined in forward flight in accordance with:

$$\begin{aligned}\Delta\varphi_i &= a_{n-1}\sin(n-1)\psi_i + b_{n-1}\cos(n-1)\psi_i +\\ &+ a_n \sin n\psi_i + b_n \cos n\psi_i +\\ &+ a_{n+1}\sin(n+1)\psi_i + b_{n+1}\cos(n+1)\psi_i\end{aligned}$$

where:

$\Delta\varphi_i$ – incremental feathering angle of i-th blade;
ψ_i - azimuth angle of i-th blade;
n – number of rotor blades;
a, b – coefficients of corresponding control harmonics.

Then at steady flight regime a multicyclic control was entered by insertion in feathering angle of each blade the IBC signal:

$$\Delta\varphi i=0.5°\sin[n\cdot(\omega\cdot t+i\cdot\Delta\psi)+\Phi],$$

where i- number of harmonic (4th, 5th, 6th),

Φ - control phase (0°…360°)

In the investigation there are considered 5 harmonics hub forces in the helicopter body axes coordinates as follows:

T - thrust; S - lateral force; H - longitudinal force.

Control amplitude was 0.5° for all cases, phase changes were with increase by 012° after each solution.

As a result we get a change of all parameters for 5th harmonic depending on control action phase. As an example fig.1 shows results of rotor blade loads for the initial control case; fig.2 – for high frequent control which changes by 6th harmonic. The pictures show three components of force in helicopter rotor blade depending on time for 2 turns of the rotor. Considering of elastic blade vibrations shows that vibrations with harmonics lower than 5th appear. It has an influence on forces that appear in the rotor.

Further analysis of calculations results is done in dimensionless form, where the amplitudes of rotor blade forces are divided to the correspondent amplitudes of 5th harmonics, that were got for the initial control:

$$\bar{A}= A_{si}/ A_{so}$$

where:

$\bar{A}$ – dimensionless amplitude of 5th harmonic of rotor forces;
A_{si} - calculation amplitude of 5th harmonic of i^{th} rotor force for one calculation case of high harmonic control;
A_{so} – calculation amplitude of 5th harmonic of i^{th} rotor force without high harmonics control.

Furthermore, analyzing calculations results we considered 5th harmonic phase displacement of forces in case of high harmonic control and without it.

Comparative calculations are performed for the 230 km/h airspeed.

Calculation results for monoharmonic control of high harmonic

At first we considered only one control harmonic – 4th, 5th and 6th harmonics of rotor control. We used action control amplitude of 0.5° for each case. Calculation results are presented in fig.3, 4, 5 in dimensionless form. Dimensionless amplitudes of 5th harmonic of rotor forces are shown in the left side of the figures. The right side presents their phase displacement related to the blade 0 azimuth.

The amplitude of 5th harmonic of forces without high harmonics control is shown as dotted line. Calculation results for the rigid blade taken from [3, 4] (for the airspeed of 230 km/h and converted to dimensionless form) are presented as small dotted lines.

Analysis of the presented results for the elastic blade in planes of bending and torsion shows correspondence to the results in [3, 4] for the rigid blades. Change of high harmonics action control phase leads to harmonic amplitude change of 5th harmonic forces. Also we see that the use of the blades elasticity leads to some differences. One of them can be explained as a difference in the value of action control phase, which is used to get minimal amplitude of 5th harmonic forces change. The second difference is in reduction of action control efficiency for elastic blade. First of all the reason for these differences is that the IBC concept control is carried out by the change of rotor blade angle of blade root which has no influence to the end part of the blade due to its elastic deformations.

Analyzing the data in fig.3 we can see that the action control has different influences on the amplitude of 5th harmonic of rotor forces. For 4th harmonic of action control 5th harmonic of rotor longitudinal force is approximately twice less for the elastic blade than for the rigid one. We also see that the phases of 5th harmonic of rotor forces, which correspond to the amplitude minimal value, in case of elastic blade are approximately the same (the range is 170°…200°). In case of rigid blade we have the opposite situation: the range of optimal phases of action control is 240°…340°. Therefore, the third conclusion from the analysis is that 4th harmonic of action control can't decrease the amplitude of 5th harmonic of rotor forces.

The phase change of 5th harmonic of rotor forces dependent on the phase of action control is presented on the left side of fig.3. The figures show that the phase displacement of 5th harmonic has approximately the same form for all rotor forces and the phase for elastic blade is the same as in case of rigid one for the minimal value of the amplitude of 5th harmonic rotor forces.

Fig.4 shows calculation results for 5th harmonic control as in case of 4th harmonic action control. The results for rotor component force in Y direction for the elastic blade correspond to the results for the rigid blade in terms of their view and phases. But the efficiency of the action control is reduced 2.5…3.0 times. The influence of the considered control on the longitudinal and lateral components of rotor force for elastic blades leads to a change of ~180° of the action control optimal phase. The ratio of the optimal phases for the longitudinal and lateral forces remains the same, i.e. optimal phase displacement between them is ~90°.

The phase change of 5th harmonic of rotor dependent on the action control phase is presented on the left side of fig.4. It shows that unlike the results for 4th harmonic of action control the figures are different for the different rotor forces. The phase displacement for 5th harmonic force in Y direction is without significant changes and differs from identical parameter for the rigid blade is ~140°. The phase displacements figures are different for the longitudinal and lateral rotor forces.

Identical figures of calculations results for 6th harmonic action control are presented in fig.5. The figures show that the control of 6th harmonic for elastic blade is more efficient for the longitudinal force compared with the rigid blade calculations. For the vertical and lateral forces efficiency of the control for elastic blade is significantly lower. This effect can be explained by the closeness of master frequency of the blade and its torsion eigen frequiency. We also see that compared with rigid blade, where the optimal phases for 5th harmonic of rotor forces were closer, for elastic blades they differ significantly.

The phase change of 5th harmonic of the rotor in dependence with an action control phase is presented on the left side of fig.5. It shows that forms of the figures differ for the different forces of the rotor.

Influence of monoharmonic amplitude of high harmonic control

The results in the previous chapter show that efficiency of high harmonic control with harmonic action amplitude of 0.5° is less than for the rigid blade. To find out what will happen if we use other amplitudes we performed parametric calculations for different action amplitudes with optimal phase control for 4th, 5th and 6th harmonics. Fig.6 shows the change of amplitude of 5th harmonic rotor forces according to the action control amplitude. Graphs for 4th harmonic control action are shown in Fig.6a, for 5th harmonic control action – in Fig.6b and for 6th harmonic – in fig.6c.

The overall effect of the influence of control action amplitude to rotor vibration loads for the elastic blades differs from the results from [3, 4] for rigid blades. There is nearly linear dependence between reducing of the amplitude of 5th harmonic rotor force and control action amplitude for rigid blade. For elastic blade vibration loads reducing effect exists in a very short range of 0°…0.5° in most cases.

The peculiarity of the presented results is that the maximum effect of 5th harmonics rotor forces reduction is reached with the small action amplitude of 0.2°…0.3°. We also found that change of control action amplitude allows us to significantly reduce rotor vibration loads. The maximum effect of reducing all the components of rotor vibration loads is reached with the help of 4th harmonic of control action (Fig.6a) as well as in case of rigid blade, but the effect is significantly lower. Elastic blade rotor vibration loads are reduced up to ~40% while rigid blade rotor vibration loads can be reduced to zero.

The maximum effect of vertical vibration loads reduction is reached with the help of 6th harmonic control action: with the amplitude of 0.3° vertical vibration load is reduced up to 55% (Fig.6c).

The maximum effect of lateral vibration loads reduction is reached with the use of 5th harmonic control action: with the amplitude of 0.7° vertical vibration loads is reduced up to 90% (Fig.6b). However, with this amplitude, the value of vertical vibration load increases approximately in 2.5 times.

Thus we can conclude that optimal value of rotor vibration loads reduction can be reached with non-high amplitudes of high harmonic control action. Yet we should highlight that the conclusions we have got correspond to the researches performed for the blades with known strength characteristics.

Calculations results for polyharmonic control for high harmonics

As calculations results for the rigid blade [3, 4] and for the elastic blade show different influences of harmonic number on 5th harmonic vibration loads values the combination of the action control harmonic amplitudes and phases can give us the optimal effect. In [3, 4] an automated method of high harmonics optimal control determining for a given flight regime for rigid blade was developed. Due to significant increase of calculation time of rotor parameters for the elastic blade task this approach was unacceptable. So, in this study we performed calculations with several combinations of action control harmonics. Fig.7 shows the results of these studies.

Fig.7.a shows calculations results for combination cases of 4th, 5th and 6th action control harmonics with optimal phase for each harmonic taken from the previous chapters. Action amplitude is the same for each harmonic. We considered two amplitudes of 0.50° and 0.25°. Figures for

the action control amplitude of 0.50° are presented in fig.7.a, and fig.7.b shows those for the amplitude of 0.25°. The figures show a change of rotor forces during the time for 2 rotor turns. We performed harmonic analysis of the results to find 5th harmonic of rotor forces and converted them to a dimensionless form. These results are presented in the table below.

Table 1

Amplitude of rotor forces **Control amplitude**	$\bar{A}_y$	$\bar{A}_x$	$\bar{A}_z$
0.00°	1.00	1.00	1.00
0.25°	1.86	0.44	0.59
0.50°	4.19	1.49	1.60

From the table above we see a summing effect of optimal variants control for 4th, 5th and 6th harmonics. We can also see from the table that the use of harmonic combination with control action amplitudes of 0.5° is unreasonable as it leads to vibration loads increase for 5th harmonic of all rotor forces. Control action amplitude of 0.25° leads to a positive effect for the longitudinal and lateral forces that are located in plane of rotation. Also it increases vibration load in plane of thrust on 86%.

Thus we conclude that the summing of control action for optimal phase of each harmonic doesn’t always lead to optimal results. The same result was obtained in ([3, 4]) for the rigid blade. It is probably reasonable to perform an optimization of the control law by the method which was developed in [3, 4] with the use of well-powered computer.

Conclusion

1. Calculations of the elastic blade considering its elasticity to bending and torsion show the same influence of rotor control signal phase as in case of rigid blades.
2. Consideration of bending and torsion for the elastic blade shows that the influence of high harmonic control on amplitudes of vibration loads is less than in case of rigid blade.
3. Calculations of the blade considering its bending and torsion elasticity show the control phases which correspond to minimal value of vibration loads.

Literature

1. Ивчин В.А., Есаулов С.Ю, Самусенко А.Г., Моделирование на пилотажном стенде снижения вибраций вертолета путем ввода в закон изменения циклического шага лопастей высокочастотных колебаний, Труды 10 форума Российского вертолетного общества, 2012г.
2. Ивчин В.А., Самусенко А.Г., Есаулов С.Ю., Моделирование на пилотажном стенде снижения вибраций вертолета путем ввода высокочастотных колебаний в закон изменения циклического шага лопастей, Вертолеты, Труды ОКБ МВЗ имени М.Л. Миля, вып. 2, Москва, "Машиностроение", 2012 г.
3. Samusenko A.G., Esaulov S.Yu., Ivchin V.A., Simulation of Helicopter Vibration Reduction by Means of Higher Harmonics Control with the Use of Flight Simulator, 38th European Rotorcraft Forum, Amsterdam, 2012.
4. Samusenko A.G., Esaulov S.Yu., Ivchin V.A., Simulation of Helicopter Vibration Reduction by Means of Higher Harmonics Control with the Use of Flight Simulator, 69th Proceedings AHS International, Phoenix, Arizona, 2013.
5. Averyanov I.O., Agamirov L.V., Ivchin V.A. The Study of the finite-difference scheme for calculating aircraft rotor strength for the transient and maneuver regimes. Scientific and Technical Conference "Gagarin Readings", 2010
6. Averyanov I.O., Ivchin V.A. Development of the calculation method for elastic rotor blade deformation in the plane of thrust, rotation and torsion by means of forth integration, Scientific Journal MGTU GA № 172, 2011
7. Averyanov I.O., Ivchin V.A. The Study of the rotor blade proper motion dynamics by the method of forth integration, Scientific Journal MGTU GA № 172, 2011
8. A.Y. Liss. The Study of the rotor in two planes bending, and torsion. Dissertation for the degree of Doctor of Technical Sciences, Kazan, 1974.

Without high harmonic control

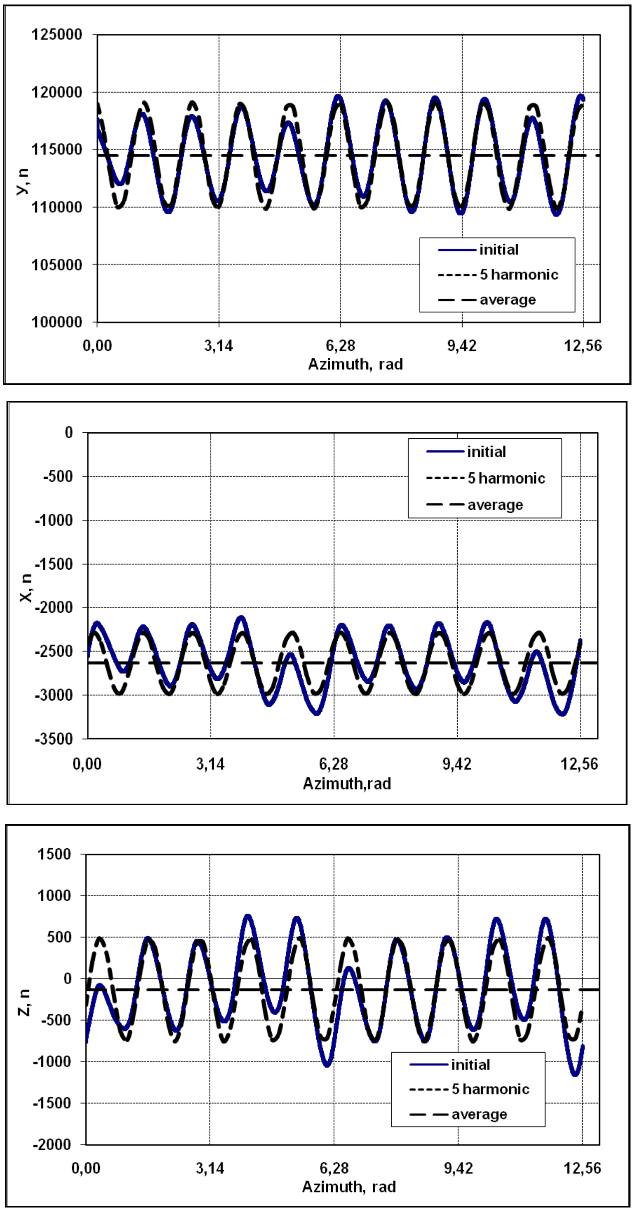


Fig. 1

6th harmonic control Δφ=0.5°

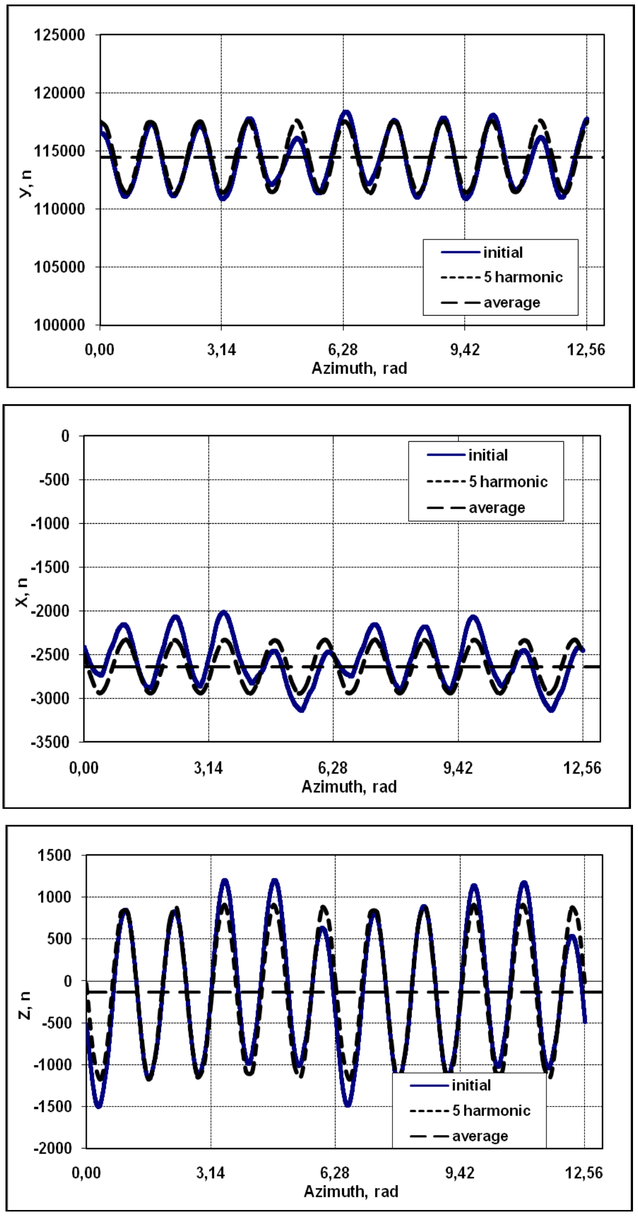


Fig. 2

Airspeed 230 km/h, 4th harmonic control amplitude Δφ=0.5°.

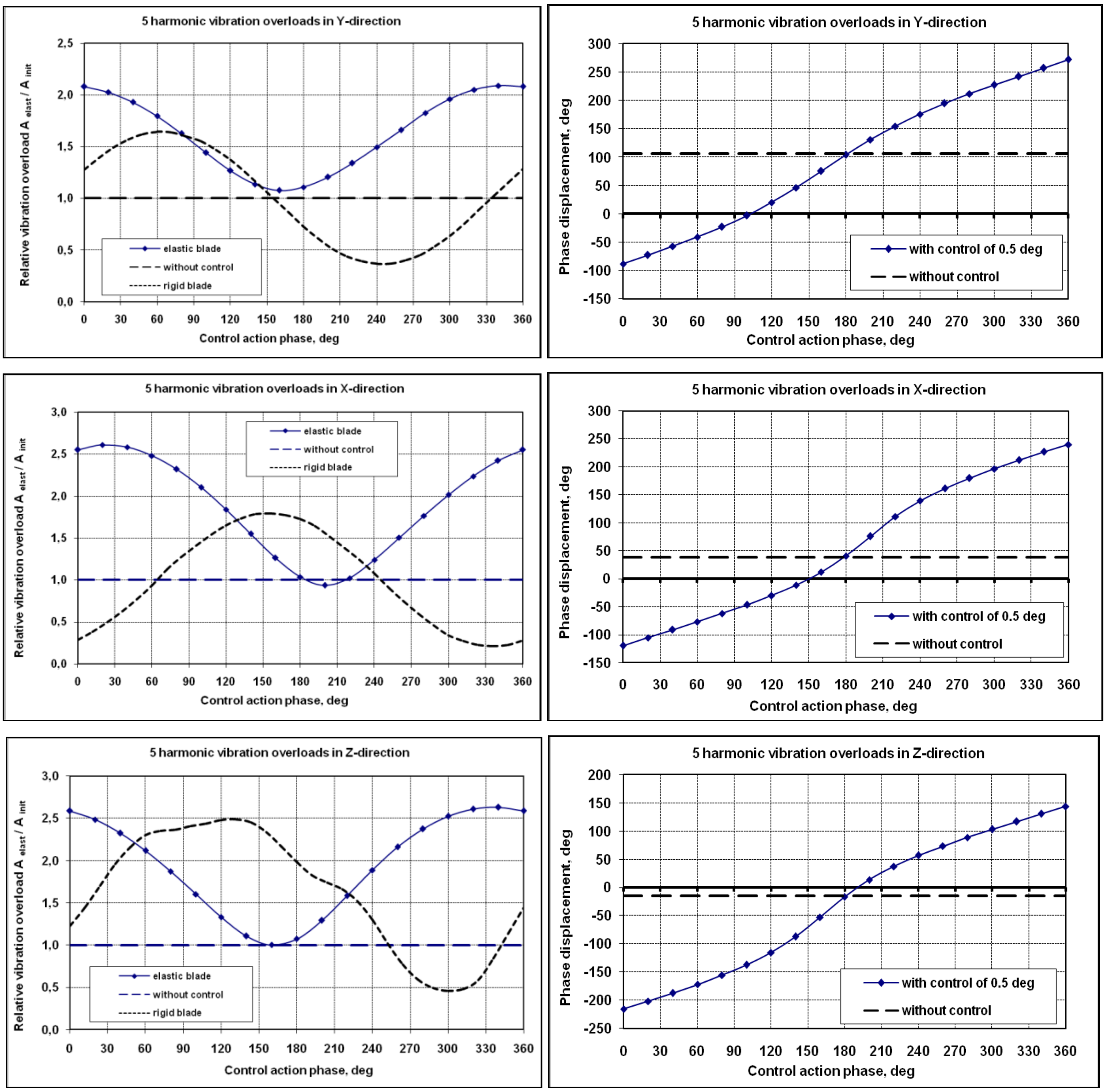


Fig. 3

Airspeed 230 km/h, 5th harmonic control amplitude $\Delta\varphi=0.5°$.

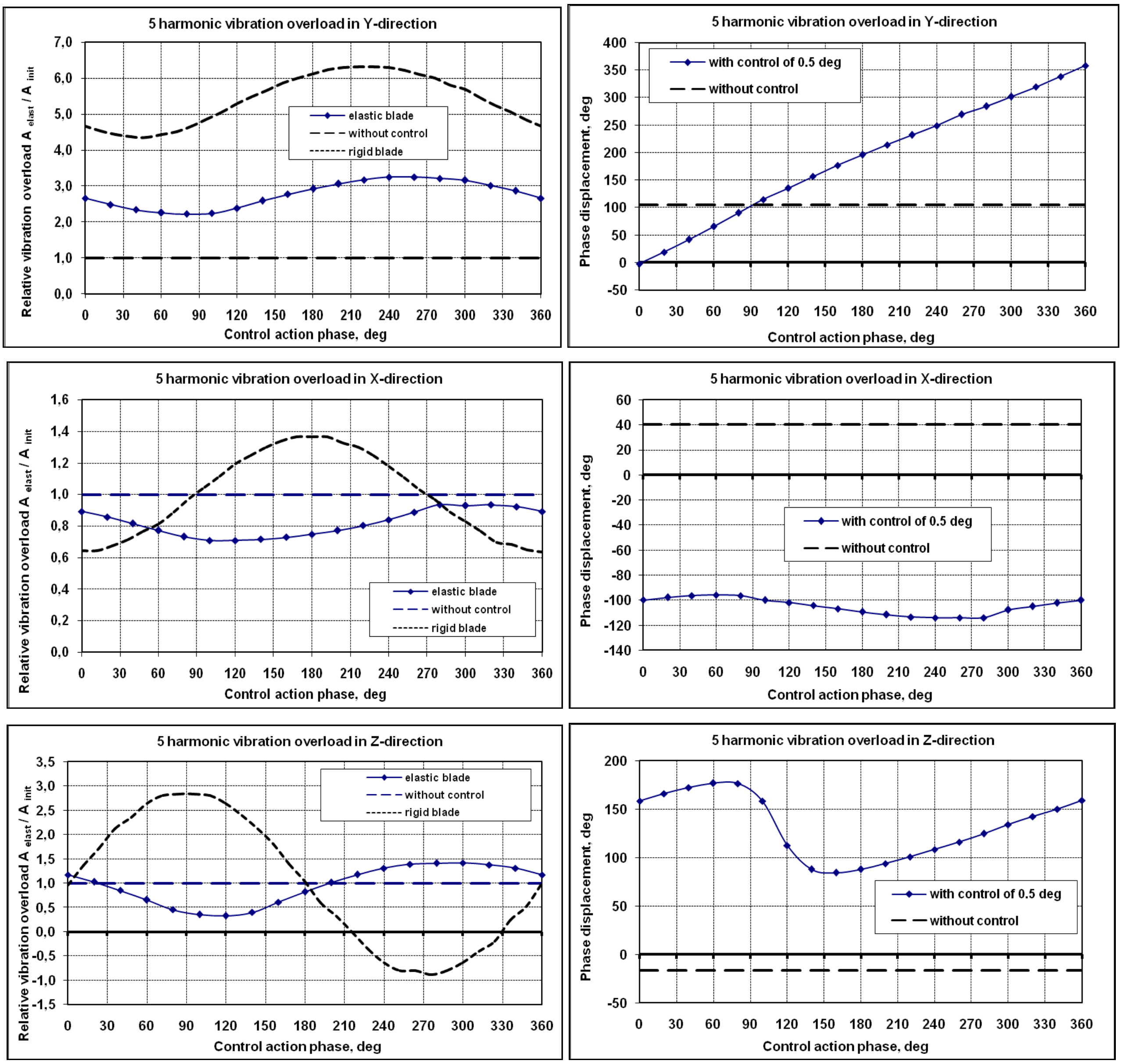


Fig. 4

Airspeed 230 km/h, 6th harmonic control amplitude Δφ=0.5°.

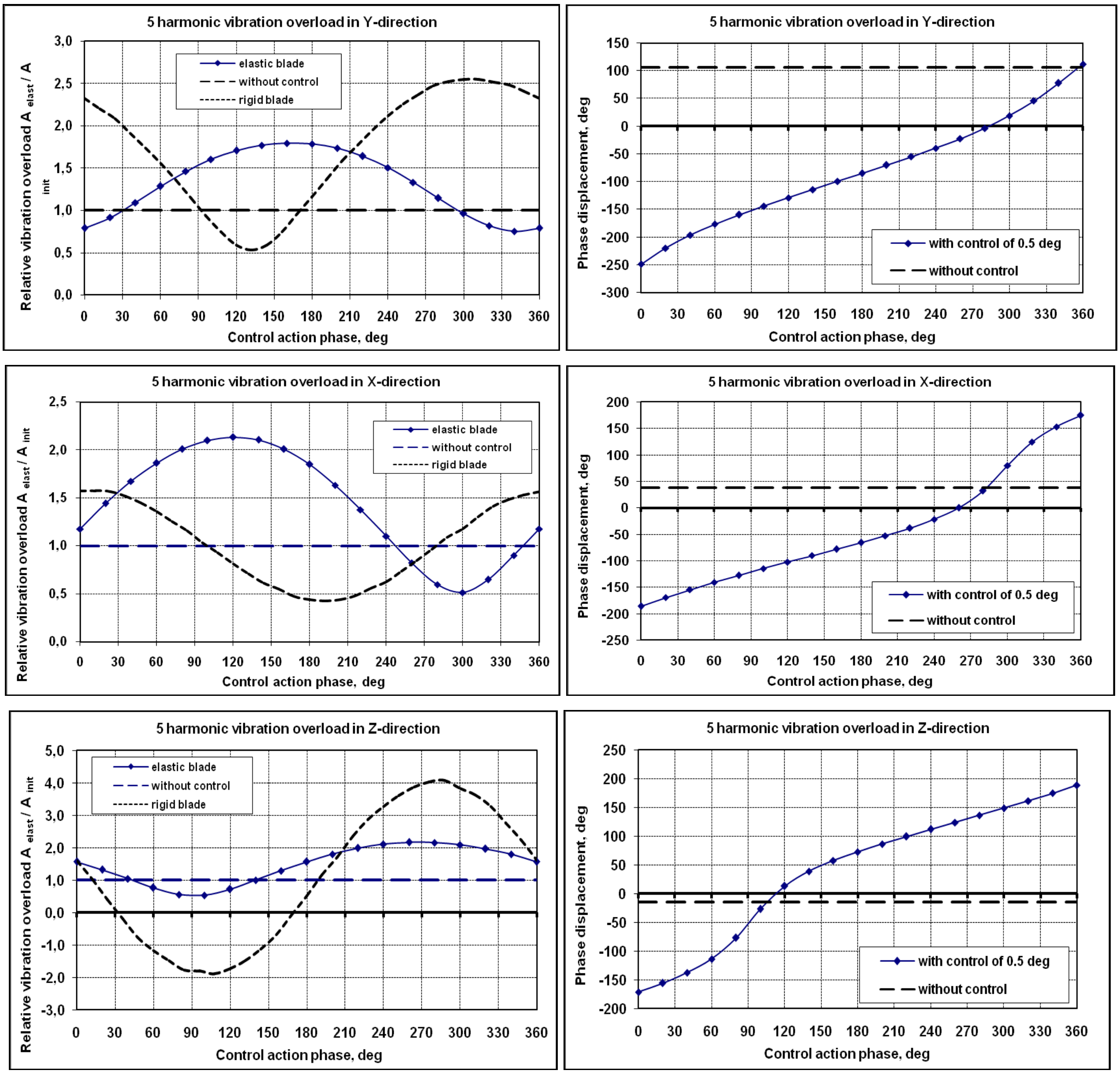
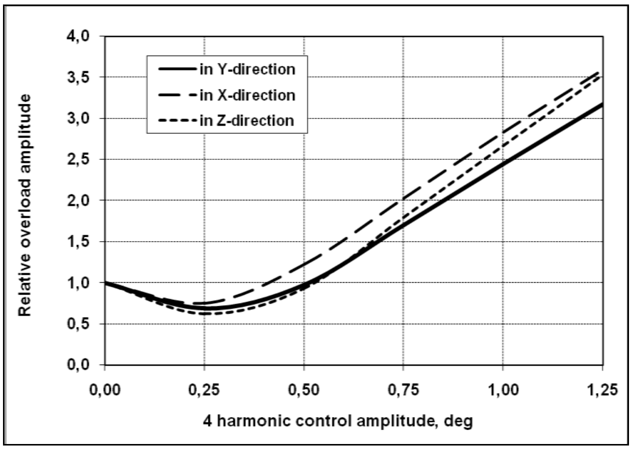


Fig. 5



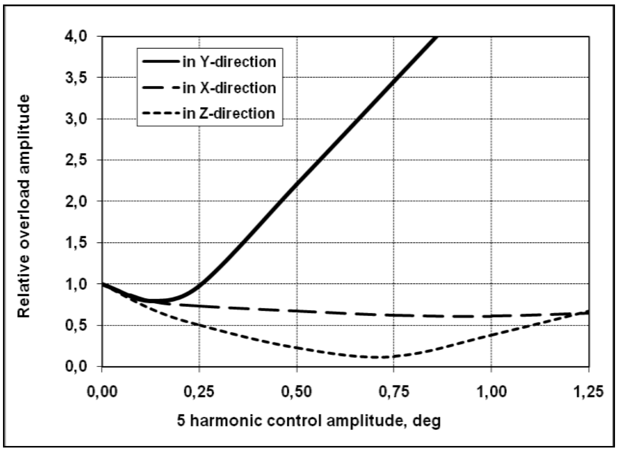


Fig. 6a

Fig. 6b

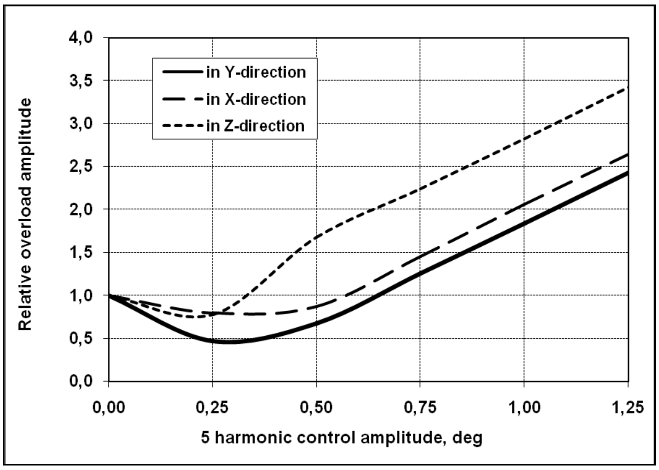


Fig. 6c

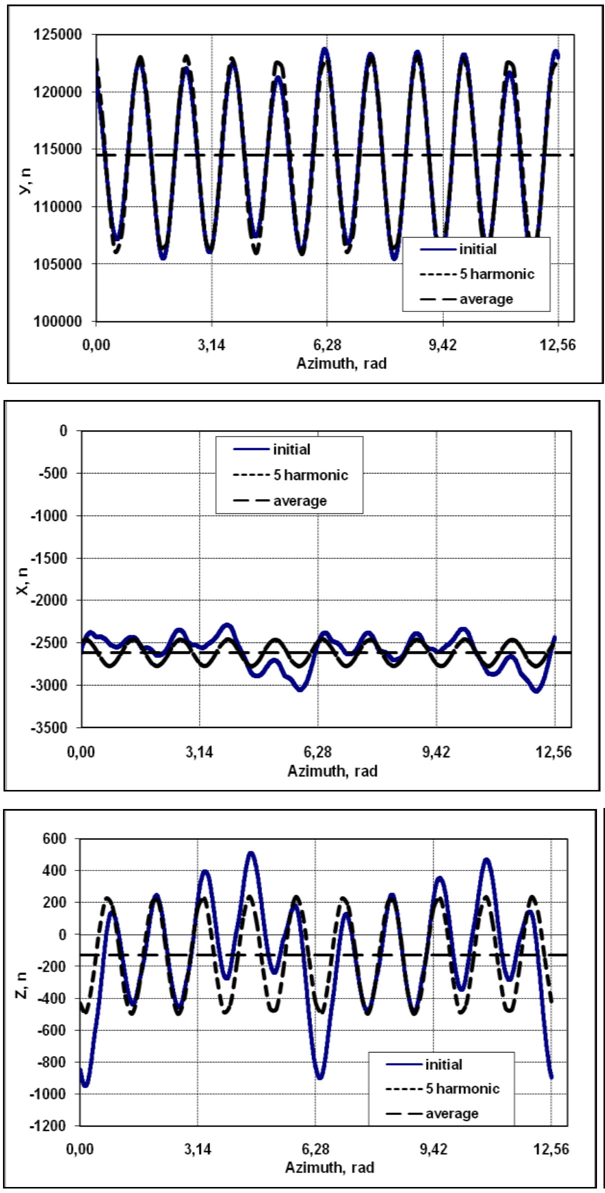


Fig. 7a

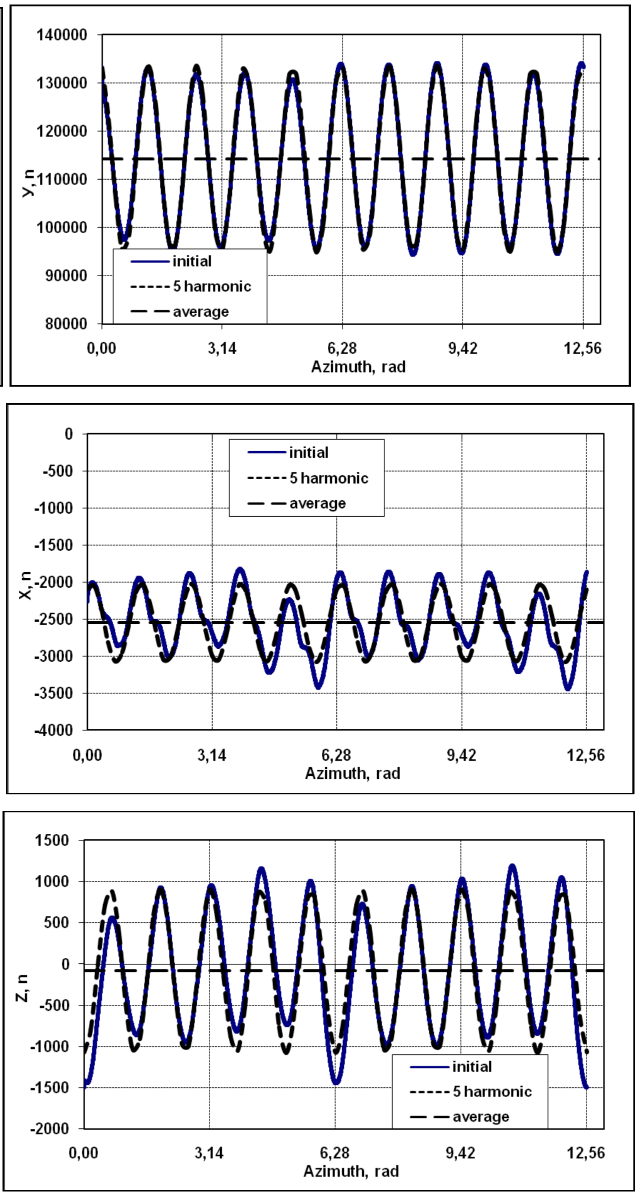


Fig. 7b