HELICOPTER DESIGN FOR HANDLING QUALITIES ENHANCEMENT

Deniz Yilmaz[1], Delft University of Technology, Delft, Netherlands
Dr. Marilena D. Pavel[2], Delft University of Technology, Delft, Netherlands
Dr. Ilkay Yavrucuk[3], Middle East Technical University, Ankara, Turkey

Abstract

This research aims to bring HQ's (Handling Qualities) assessment according to ADS-33E-PRF into early stages of helicopter design process, namely late conceptual and early preliminary design phase. Effects of three design parameters, namely disc loading, rotor tip speed and blade loading coefficient, on bandwidth phase delay criterion of the ADS-33E-PRF for pitch channel is investigated for the hover condition flown by a 10 degrees of freedom Bo-105 like simulation model. After setting practical design constraints, the variation of each design parameter has been plotted in bandwidth-phase delay graphs. The results indicate that disc loading eventuated as the "grouping" parameter, forming isoline maps for tip speed and blade loading coefficient. Furthermore, the different sets of disc loading isoline maps generate a curved non-linear pattern, inherently with a three dimensional translation. High disc loading with high tip speed and low blade loading coefficient configuration resulted in Level 1 handling qualities. Low disc loading cases provide a wide spectrum of phase delay values with a small interval of possible bandwidth, visa versa for high disc loading case. The paper provides an insight into the design space available in means of bandwidth-phase delay analysis in hovering flight.

Nomenclature

ω_{180} = Frequency @180 degrees phase angle difference [rad/sec] defined in ADS-33E-PRF [1]

$\Delta\Phi_{2\omega_{180}}$ =Phase angle difference [deg] defined in ADS-33E-PRF [1]

ω_{BW_θ} = Pitch attitude bandwidth [rad/s] defined in ADS-33E-PRF [1]

$\tau_{p\theta}$ = Phase delay [s] defined in ADS-33E-PRF [1]

W = Gross weight [lb]

R = Main rotor radius [ft]

C_T = Thrust coefficient [-]

σ = Main rotor solidity [-]

Ω = Main rotor angular velocity [rad/s]

1. INTRODUCTION

Especially in the last decade, the increasing needs of complex and demanding mission profiles in recent helicopter flight envelopes lead the idea of improving handling qualities (HQ's) and safety of helicopter missions. Interests of helicopter community have been subjecting their focus more than before on favorable handling quality characteristics and their application to multidisciplinary design processes. For the general case, handling quality assessments were threatened as a secondary design key objective but it turned out to be that more potential is hidden in this relatively degraded field when

---

Paper presented at the 35th European Rotorcraft Forum, September 22-25, 2009, Hamburg, Germany

[1] PhD candidate, TU Delft Aerospace Engineering Department, D.yilmaz@tudelft.nl

[2] Assistant Professor, TU Delft Aerospace Engineering Department, M.D.Pavel@tudelft.nl

[3] Faculty Member, METU Aerospace Engineering Department, yavrucuk@metu.edu.tr

helicopter mission effectiveness is considered to be an important goal for the overall design and life-cycle of helicopters. With the developing multidisciplinary perspectives, considerations and computer processing abilities, design engineers are more capable of integrating various disciplines together into one complementary design process. Therefore, handling qualities become more apparent in the whole picture of design progress. Not only cumulative importance but also the assessment time in the helicopter design schedule is now a key item for handling quality considerations.

As a general approach, helicopter preliminary design methodologies mainly focus on weight and performance characteristics according to the required mission definitions [2]. Also, configuration and sizing processes are mainly constrained by performance based criteria [3]. Even though these criteria are mandatory for overall helicopter mission effectiveness; one of the weak considerations during the initial stages of helicopter design concerns the HQ's characteristics. Commonly, HQ's assessments are applied after preliminary design, when most of the specifications and configurations are already set. In case of undesired levels of HQ's, helicopter is subjected to additional flight tests, controllers, equipments, etc., which leads to considerable increase in project cost, delay and man power [4]. To overcome this deficiency, the present paper proposes to apply HQ's assessments as early as possible during design process.

One of the most updated and appreciated techniques for helicopter handling quality assessment is the ADS-33E-PRF requirement specification [1], which is intended to cover land based rotorcraft with primary missions ranging from scout, attack to utility and cargo. In this study, criteria of this approach are taken into account in means of handling quality grading. More specifically, bandwidth - phase delay criterion is focused on during handling quality analysis.

In literature, one of the earliest studies on integration of handling qualities considerations during helicopter design is the work of Chen and Talbot [7]. They investigated the effects of various rotor parameter deviations on helicopter handling characteristics in nap-of-the-earth (NOE) flight. Design parameters were selected to be flapping hinge restraint and offset, the blade Lock number and pitch-flap coupling parameters with various combinations as teetering, articulated and hingeless configurations during a set of maneuvers. The paper aims to achieve a general mapping of damping and control sensitivity while evaluating cross-coupling and pitch-flap couplings during NOE flight. In 1986, as a final report of the winner team of American Helicopter Society (AHS) design competition of 84/85, Berry and Schrage [8] published a paper focused on helicopter design for maneuverability and agility to accomplish the specified triangular flight route track. Altering basic rotor design parameters with optimization resulted in an ideal helicopter configuration to complete the track within minimum time. Later in 1989, a remarkable paper about design parameter sweeping for maneuverability and agility was published by Olson and Scott [10].In the study, various helicopter design parameters were altered and predefined maneuvers were performed. Maneuverability and agility were defined according to maneuver specific accomplishments. Each parameter was changed within the physical design limitations for each maneuver. Then, sensitivity maps were prepared to show influence of design parameter on each maneuver with the penalty of gross weight increment. It was concluded that some agility and maneuverability characteristics (AMC) are highly depend on the chosen maneuver. Therefore, some parameters had positive effects on AMC for one maneuver, whereas they had degrading effect for another maneuver. Hence, good and bad optimizers were defined to emphasize these inter-coupling characteristics in terms of AMC affects. Moreover, collapsing design parameter influence charts to a more global denominator, which was thrust-to-weight ratio in their paper, was performed. Finally, guidelines were supported to designer according to design parameter sweep results of AMC for the selected maneuvers. In this current paper, the same procedure is followed.

Fradenburgh [12] presented a basic optimization study, which was on altering basic design parameters to obtain a more silent helicopter when compared to baseline. The aim was reducing tip speed while keeping other characteristics of the helicopter as constant as possible. Resulting optimum design configuration was basically obtained by increasing radius, number of blades and decreasing rotor angular velocity. Weight increment was selected as a fundamental consideration with auto rotational, power loading and other design constraints and cross checks. This study was an important example of tweaking design parameters to achieve desired characteristics for a preset helicopter configuration. In 1994, Celi and Spence [16] published a paper that describes a new method for calculating the sensitivity of rotating blade root loads and hub loads to changes of blade design parameters using a chain rule differentiation approach.

Sahasrabudhe and Celi [13] investigated a multidisciplinary optimization of the rotor and flight control system by using aeroelastic stability and handling qualities as constraints. The design variables were flap and lag stiffness of the rotor, the flap-lag elastic coupling factor and control system gains. During the optimization, some constraints and techniques are chosen as to be pole placement, frequency response spectrums and time histories of the response to applied pilot inputs. Conclusion of the study was that lower control effort could be achieved by designing the rotor and flight control system simultaneously rather than first the rotor and following the control system. In 2002, Fusato and Celi [14] analyzed the sensitivity of the ADS-33 quickness criteria and maneuver loads to changes for selected fuselage, flight control system and rotor parameters. Their objective was to predict the fundamental effects of selected design parameters on the handling qualities such that they set ADS-33E Level 1 handling qualities requirements as constraints. For most of the selected design parameters the results were promising, but the flight control system parameters that affected trim and rotor mode shapes were still a problem. They rearranged optimization techniques and extended their work with the new semi-analytic optimization routine. [15].The aim was to find primary design variables to optimize for better progressive lag mode damping. The conclusion was that the blade torsion stiffness was the most dominant variable to achieve the objective, which yielded as increasing the mode damping about 90 percent. They also concluded that design optimization is a highly coupled multidisciplinary process with the need of great computing power, which was lowered by using semi analytical gradient method during the optimization.

In 2003, Celi [17] focused on ADS-33 quickness constrained design optimizations by using inverse simulation methods. The aim of the optimization was finding the configuration which has the optimized handling quality grade during the inversely simulated maneuvers. Especially for the pitch attitude quickness, great agreement with flight test data encourages the application of this methodology to various maneuvers supported by the trajectory generator. Continued in 2005, Celi [18] extended his inverse simulation based methodology to construct quickness maneuvers with preassigned values of the attitude change. Consequently, this methodology allows systematic parameter change for the desired family of trajectory. As an example, limitations for the achievable roll quickness is found to be depend on lift coefficients of the front and rear part of the main rotor tip path plane.

To sum up, previous studies can be grouped as maneuverability oriented and optimization based considerations of design variables. On the other hand, the aim of this paper is bringing ADS-33 bandwidth phase delay criterion to very early stages of design to enhance the resulting handling quality. Instead of subsequent design parameters (e.g. cross-coupling terms, blade torsional stiffness, lead-lag mode damping, etc.), basic initial design parameters (disc loading, blade loading coefficient and tip speed) are chosen to be deviated within the available design spectrum to observe their effect on handling quality ratings for the selected maneuver. Next section shows the methodology followed to investigate these influences of primitive design parameters on handling quality ratings.

2. METHODOLOGY

In this study, a nonlinear mathematical helicopter simulation model of the Bolkov Bo-105 developed at Delft University is used as baseline model [5].This helicopter model includes 10 DoF (Degrees of Freedom): 6 DoF for body rotational and translational dynamics and 4 DoF for main rotor regressing flap and lead-lag dynamics and uniform inflow. The general methodology proposed for handling qualities enhancement is presented in Figure 1. For this methodology, as for the first step, the helicopter simulation model is used to perform a series of representative flight maneuvers within the ADS-33E-PRF definitions and constraints. The sensitivity of each maneuver to basic helicopter design parameters (such as disk loading, tip speed, etc) is established by varying each parameter independently. In a second step, the variation trends of the maneuver design parameters are “collapsed” to one common parameter variation which serves as basis for maneuver design. The design trends with maneuver handling qualities are then plotted in design trade offs for handling qualities enhancement. Finally, general design guidelines are elaborated for improving handling qualities characteristics within imposed constraints.

To exemplify the methodology elaborated, the paper analyses first the ADS-33 bandwidth phase delay criterion (BPD). “The bandwidth is that frequency beyond which closed-loop stability is threatened.” [6].The point where the closed-loop pilot-aircraft system becomes unstable is commonly referred to as the crossover frequency. According to ADS-33, BPD has two important parameters: bandwidth and phase delay. The higher the bandwidth, the larger will be the helicopter’s safety margin in high gain tracking tasks and more qualified the pilot response to fast control inputs. Generally, the bandwidth criterion is a good predictor for a PIO prone system. Figure 2 represents the graphical definitions of required frequency domain parameters for obtaining the corresponding phase delay, as shown in Equation (1).

$$(1) \qquad \tau_{p\theta} = \frac{\Delta\Phi_{2\omega_{180}}}{57.3(2\omega_{180})} \text{ [sec]}$$

For this research, maneuver performance specifications of hover condition described in ADS-33E-PRF for Degraded Visual Environment (DVE) is set as the objective flight condition for the handling qualities assessment. Level boundaries of BPD for this chosen case are shown in Figure 3.

To study Handling Qualities levels within the ADS-33 bandwidth criterion, the simulation model is linearized and subjected to 100ms time delay in pilot input for a pitch channel step input applied from hover condition. It is well known that the time delay has a remarkable influence on the bandwidth characteristics of the helicopter [1], [5] ,[6]. Hence, 100ms time delay is found to be a reasonable value for a helicopter like Bo 105.

To bring the handling qualities assessment into design at as early stages as possible, the paper has chosen the following design parameters for analysis: disc loading (DL), blade loading coefficient (BL) and tip speed V_{tip} defined as shown in equations (2), (3) and (4) respectively.

$$(2) \qquad DL = \frac{W}{\pi R^2} \text{ [lb/ft}^2\text{]}$$

$$(3) \qquad BL = \frac{C_T}{\sigma} \text{ [-]}$$

$$(4) \qquad V_{tip} = \Omega R \text{ [ft/sec]}$$

where W=helicopter gross weight, R= rotor radius, C_T= thrust coefficient, σ=blade solidity, Ω=rotor rpm. To keep design variables within structural, performance and aerodynamic constraints, various limiting conditions are set according to references [2],[3],[6],[9]. Therefore, while providing design flexibility to the designer, it is also aimed to set general constraints that keep the overall approach within reasonable configuration range. Also, the gross weight, the maximum forward velocity and the number of blades are set constant during the analysis for all design configurations. This will make the design trends obtained relatively comparable. As an example of design restriction, tip speed variation is forced to be within the boundaries of Figure 4.

After setting reconfigurable design parameters, a whole range of usable design parameters is obtained. This set of available design points are demonstrated in Figure 5 with various chord, main rotor angular velocity and radius. As can be seen in the figure, patterns are recognizable in the shape of layers for each set of rotor design parameters analysed. Imposed constraints are thought to be a reason of layer shaped behavior of design parameter set.

For each design point, helicopter simulation model is trimmed, linearized and analysed for bandwidth criterion. Gathered results are organized in design parameter sensitivity charts in order to provide designers with ADS-33 handling quality analysis.

3. RESULTS

Before concentrating on individual design parameters, it is thought to be a good idea to represent all bandwidth analysis results in one graph for the whole set of parameters. The trend of overall design parameter sweep is shown in Figure 6. It is observed that there is a pattern with varying set of disc loadings, which will be called constant disc loading design map throughout the paper. To investigate the trend, the whole range of design configurations is split into three sub-categories: low, moderate and high constant disc loading design maps. Such set of analysis is shown in Figure 7, in which high, moderate and low disc loading cases are grouped by circle, diamond and delta markers respectively. The trend of the increasing disc loading is also shown in the same figure. It is noticed that instead of a linear pattern variation, there is no trend in the shifting of the constant-disc-loading design maps, at most, a continuous path variation can be suggested. Also, it is noted that higher disc loading resulted in a map of longer interval bandwidth variation as compared to the low disc loading cases. However, phase delay interval variation of the high disc loading case is relatively small when compared to the low disc loading case. Hence, high disc loading provides a large interval for bandwidth variation, which may provide more design space for PIO prevention. On the other hand, small phase delay interval may result in reduced space for response delay considerations. Vise versa for the low disc loading case. In terms of handling qualities leveling, the pattern of the increasing disc loading cases shows that the general trend of map is shifting. It should be observed that: 1) these maps include various design points within the constant disc loading design maps and 2) the handling qualities level of a design point depends of its position within the map. For example through Figure 7, it is observed that some design points within high disc loading map have better handling qualities grades (level 1) than the ones of low disc loading case (level 2) , whereas some design points in the same high disc loading map have worse handling qualities grades (level 2) than the ones of low disc loading case. In fact, to reach Level 1 handling qualities, one must have a high disc loading but this causes extension of the map horizontally, which means dependency on the position of the design point on the map, which may also result in a worsening in handling quality level. Therefore, each map should be treated individually, investigating the positioning of the design points in the constant-disc-loading map.

Next subsections will investigate each disc loading case. During the elaboration of each case, deviations of tip speed, blade loading coefficient and handling quality levels are shown as deviations from the available minimum corresponding design point within the analyzed disc loading case.

3.1. High Disc Loading Map

High disc loading case refers to map of design parameters with disc loading of 6.225 lb/ft^2. The corresponding design map is plotted in Figure 8. In the design map area, tip speed and blade loading coefficients are varied. The trend of variation of each parameter is shown in Figure 9 with isolines. This figure indicates that for the same tip speed, increasing the blade loading coefficient results in better handling qualities grading in means of phase delay-bandwidth criterion. Also, for the same blade loading coefficient, increasing tip speed results in better handling qualities. One of the observations here is the level of improvement in handling qualities deviation. This is represented in Figure 10. Since both isolines create a rectangular gridded flat surface, Figure 10 can be assumed to be in 2-D form. As the figure implies, variation of tip speed has a higher influence on handling qualities grading than the variation of blade loading coefficient, while keeping the other design parameter constant. In the high disc loading case, the design point with best handling qualities is on the highest tip speed isoline with low blade loading coefficient. The worst handling qualities grade belongs to the design point with lowest tip speed and high blade loading. Even tough reading of map characteristic does not lead to strict conclusions; it can be deemed that the effect of tip speed is more dominant than blade loading for the high disc loading case.

3.2. Moderate Disc Loading Map

Moderate disc loading case refers to map of design parameters with disc loading of 4.741 lb/ft^2. The corresponding design map is plotted in Figure 11. In the design map area, the tip speed and blade loading coefficients are varied and trends of each parameter are shown with isolines in Figure 12. Unlike the high disc loading case, this case has a curved trend with unequally distributed design points. As already observed from the general trend of Figure 5, moderate disc loading locates in the shape shifting area of overall trend. Therefore, it is not a surprise to expect this curved behavior of parameter pattern. On the other hand, it is interesting to observe that the pattern seems to cover a 3-D planar semi-cone surface, as presented in Figure 13. As a consequence of unequally distribution with curved patterns, design parameter effects on handling qualities improvements are represented in Figure 14. One key feature to observe here is the curved patterns of tip speed and blade loading deviation, which depends in this case on the tip speed. To enhance handling qualities in terms of bandwidth-phase delay criterion with a moderate disc loading design, designer should consider a relatively higher tip speed with a higher blade loading coefficient. Unlike the high disc loading, in moderate disc loading case both tip speed and blade loading coefficient play a vital role in handling quality improvements, in terms of bandwidth-phase delay criterion. Important remark here is that the deviations of handling qualities grades are relatively small when compared to the high disc loading case. Referring to Figure 7 again, it can be concluded that handling qualities improvement in moderate disc loading design map is remarkably small when compared to the case of low disc loading and especially high disc loading.

3.3. Low Disc Loading Map

Low disc loading case refers to map of design parameters with disc loading of 3.885 lb/ft2. Corresponding design map is plotted in Figure 15. In the design map area, tip speed and blade loading coefficients are varied. The trends of each parameter variation are shown in Figure 16 with isolines. From the figure it is observed that increasing tip speed degrades handling qualities along blade loading coefficient isolines. Similarly, higher blade loading coefficient lowers the handling qualities on tip speed isolines. This is found to be interesting, because unlike other cases, the low disc loading case has its best handling qualities grades with medium rotor tip speeds and low blade loading coefficients. The corresponding HQ's leveling graph is expected to be like in Figure 17 . Degrading effects of both design variables are quite low when compared to the deviations of other disc loading cases.

To sum up, highest disc loading map has a wide "horizontal" part but with a narrow vertical side, which refers to bigger bandwidth interval variation within small phase delay possibilities. On the contrary, lowest disc loading map has a high vertical interval variation with small "horizontal" part, which means less bandwidth choices with more phase delay possibilities. In means of handling qualities grading, highest disc loading provides long range of HQ variation interval, whereas moderate and low disc loading considerably limited the HQ deviation. Therefore, to have the flexibility of varying handling qualities according to different design configurations; designer should consider having a higher disc loading. But it must be noted that higher disc loading map also contains design points with almost worst handling qualities too. Besides, moderate and low disc loading maps result in relatively close handling quality grades due to their limited bandwidth design flexibility. Thus, designer may have a more clear idea of resulting handling quality grade if he/she chooses a moderate or low disc loading, since varying other initial design parameters does not effectively alter the handling quality level from one design point to another.

3.4. Deviant Disc Loading

Grouping whole design parameter distribution into constant disc loading maps resulted in apparent pattern behavior of design point groups. However, it is also important to keep other variables constant and observe the effect of disc loading variation. Figure 18 is plotted to exemplify this situation. It can be concluded that the handling qualities of design point pairs, i.e. points which have different disc loading but the same tip speed and blade loading coefficient, are almost the same. Main effect of the disc loading deviation is the increase in phase delay in the BPD graph. This dominant "vertical" behavior is similar to low disc loading case in terms of high phase delay spectrum. It must be noted that deviating disc loading is performed for the same tip speed and blade loading cases, shown in Figure 18, hence each case has its own characteristics. Eventually, each deviation case is relatively unique due to corresponding tip speed and blade loading coefficient values.

4. CONCLUSION

In this research, the question "How can one aid the helicopter designer in means of enhancing handling qualities in conceptual design" is tried to be answered. Therefore, the effects of design parameters variations on helicopter handling qualities are investigated. At the end, it is aimed to provide guidelines to the designer such that he/she is supposed to have a basic idea of the corresponding handling quality ratings of the helicopter being designed, beginning from early stages of design.

Simulated helicopter base model is similar to Bo105, 10 degrees of freedom helicopter with coupled regressive flapping and lead-lag dynamics. As for the handling quality assessment technique, bandwidth phase delay criterion of ADS-33E-PRF is used. Design parameters to be varied are chosen as disc loading, blade loading coefficient and tip speed due to their early involvement in the design process. Model is trimmed and linearized for hover case and subjected to handling qualities analysis in each design point. Design parameters are chosen from the ones which satisfy the conditions of available points within the design boundaries formed by the structural, performance and aerodynamic constraints.

Although it was aimed to collapse design deviation data into one common denominator parameter, deviant behaviour of the design parameters make it concealed. Hence, this study keeps the guidelines for the design parameters swept for handling qualities level enhancement.

After plotting corresponding bandwidth phase delay values in HQ rating chart for the entire range of variation of design points, it is seen that the design points follow a certain pattern. Further, it is observed that design points with the same disc loading values form a map. Then, it is decided to recompose the BPD ratings of design points to arrange a collapsed map distribution. Each map is treated individually. Especially, analysis of three maps are included in this paper due to their diverse characteristic, i.e. low, moderate and high disc loading cases. Comprehensive analyses show that:

1. High disc loading case has the best handling qualities (Level 1), however almost the worst handling qualities (mid Level 2) too. Not only disc loading, but also locations of design points within the

map effectively determine the handling qualities ratings of the designed helicopter. In high disc loading case, tip speed is the dominant parameter, which influences the handling qualities level remarkably for the same blade loading coefficient conditions. Long range of bandwidth possibilities is a plus for design, especially for further PIO considerations.

2. Moderate disc loading case has an interesting pattern implying a 3-D map behavior. When compared to other disc loading cases, this one has the smallest interval for handling qualities ratings, both for bandwidth and phase delay. Even tough this case has the most limited area in BPD chart; it is the 3-D translational part of the overall disc loading cases. Whole moderate disc loading map has mid Level 2 handling qualities with limited bandwidth and phase delay.

3. Low disc loading case provides the longest range of phase delay possibilities, but limited bandwidth values. Handling quality level of this case is better than the moderate one, but still limited in Level 2. Unlike other cases, increasing tip speed has a degrading effect on HQ ratings of the design points. Moreover, low blade loading coefficients also ended up with better handling quality grades.

A brief summary table is shown in Table 1, in which comparative arrows are used to indicate relative effects of design parameters for each case. Each disc loading case has both, advantages and disadvantages, in terms of bandwidth, phase delay design flexibility and handling quality grading. For the investigated ADS-33 bandwidth phase delay criterion during hover condition, the best handling qualities of all design parameter points belong to highest disc loading with highest tip speed and lowest possible blade loading. The worst HQ grade appeared to be in relatively high disc loading with moderate tip speed and blade loading coefficient. Therefore, it can be emphasized that high disc loading cases do not guarantee best handlings qualities, but it is the only case to provide the opportunity of having enhanced HQ ratings. Moreover, high tip speed also has as a positive impact on better handling qualities achievement, especially for high disc loading cases. Although good hover performance requires low disc loading, it should be considered that the helicopter configurations are distorted versions of Bo105, which already has the highest disc loading value in its class. Hence, the trend of the disc loading should be considered as lowering from the base value, which is already about 6.2 for Bo 105 [11].

The design guidelines presented here are derived from the bandwidth phase delay criterion of ADS-33 analysis for hover case with the variations of basic and initial key design parameters. For forward flight or maneuvering cases, total approach trend may completely change. In addition to that, design parameters share variables which are also included in other parameters, cause “conflicts” for different maneuvers. This phenomenon was already recorded in the literature and these inter-coupled design parameters are reported as “poor optimizers” [10]. The scope of this research is not optimizing or defragmentation of design parameters; instead, it is aimed to have a handling qualities understanding perspective. It is strongly recommended to research similar HQ assessment for set of various maneuvers to have a general idea of the whole flight envelope effects of the key design parameters on BPD criterion. Finally, this study should be addressed as a first step of understanding influence of initial key design parameters on handling qualities. Doing the same HQ assessment by using complete optimization procedures for extended flight envelope with all possible maneuver scenarios may provide an overview of the whole design space available but this paper is just the starting point.

5. REFERENCES

[1] Anon., “Handling Qualities Requirements for Military Rotorcraft,” Aeronautical Design Standard 33 (ADS-33E-PRF), US Army Aviation and Missile Command, Mar. 2000.

[2] Prouty, R. W., Helicopter Performance, Stability, and Control ,Krieger Publishing Company, 1995

[3] Leishman, J.G., Principles of Helicopter Aerodynamics, Cambridge Aerospace Series, 2000

[4] Yue, A., Postlethwaite, I. , Improvement of helicopter handling qualities using H-infinity optimization, IEEE Control Theory and Applications, IEE Proceedings D May 1990

[5] Nguyen A.E., The Development of a Body-Flap-Lag Model for Rotorcraft-Pilot Couplings Investigation, MSc Thesis Report, August 2008

[6] Padfield, D.G., “Helicopter Flight Dynamics: The Theory and Application of Flying

Qualities and Simulation - Modeling", Published by Blackwell Publishing, 2007

[7] Chen R.T.N., Talbot P.D., "An Exploratory Investigation of the Effects of Large Variations in Rotor System Dynamics Design Parameters on Helicopter Handling Characteristics in NoE Flight "- 33rd Annual Forum of the American Helicopter Society, Washington D.C. – 1977.

[8] Berry J.D., Schrage D. Rotor Design for Maneuver Performance - 12th European Rotorcraft Forum. - 1986.

[9] Johnson W., " Helicopter Theory", New York Dover Publications, 1994

[10] Olson J.R., Scott M.W., Helicopter Design Optimization for Manoeuvrability and Agility - 45th Annual Forum of the American Helicopter Society. - 1989.

[11] Stepniewski W.Z., A Comparative Study of Soviet vs. Western Helicopters Part I: General Comparison of Designs, NASA Contractor Report 3579, 1983

[12] Fradenburgh E.A., "The first 50 years were fine, but what should we do for an encore?" The 1994 Alexander A. Nikolsky Lecture, 50th American Helicopter Society Annual Forum, 1994.

[13] Sahasrabudhe V. Celi R., Tits A. "Integrated Rotor-Flight Control System Optimization with Aeroelastic and Handling Qualities Constraints" - Journal of Guidance Control and Dynamics, Vol. 20, No. 2. - Mar-Apr 1997.

[14] Fusato D., Celi R., "Design Sensitivity Analysis for ADS-33 Quickness Criteria and Maneuver Loads." - 2002.

[15] Fusato D., Celi R. Multidisciplinary Design Optimization for Aeromechanics and Handling Qualities - 28th European Rotorcraft Forum, Bristol UK. - September 2002.

[16] Spence A.M. Celi R. Efficient Sensitivity Analysis for Rotary-Wing Aeromechanical Problems - 34th Structures, Structural Dynamics and Materials Conference. - 1993.

[17] Celi R.,Calculation of ADS-33 Quickness Parameters with Application to Design Optimization - 29th European Rotorcraft Forum, Friedrichshafen, Germany. - September 2003.

[18] Celi R., "Simulation and Analysis of ADS-33 Quickness Maneuvers for an Articulated Rotor Helicopter", AHS 61st Annual Forum,Grapevine, TX, 2005

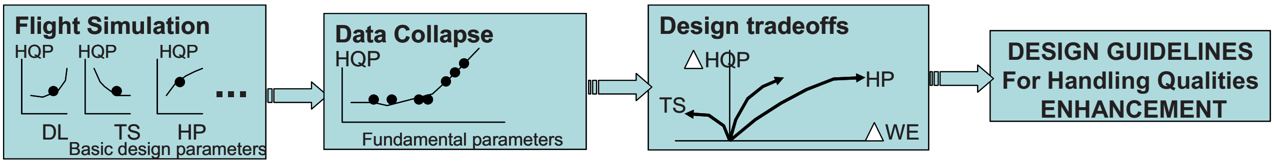

Figure 1 : *Approach used for handling qualities enhancement in helicopter design*

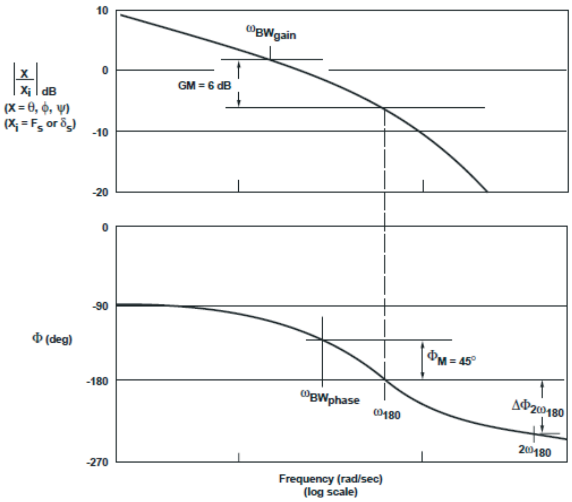

Figure 2 : *Definition graph for phase delay and bandwidth in ADS-33E-PRF [1].*

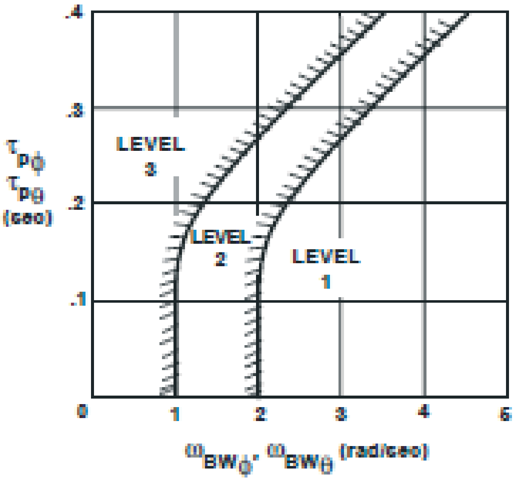

Figure 3 : *Pitch (roll) phase delay versus bandwidth handling qualities requirement graph for small amplitude pitch (roll) attitude changes during hover/low speed flight defined in ADS-33E-PRF [1].*

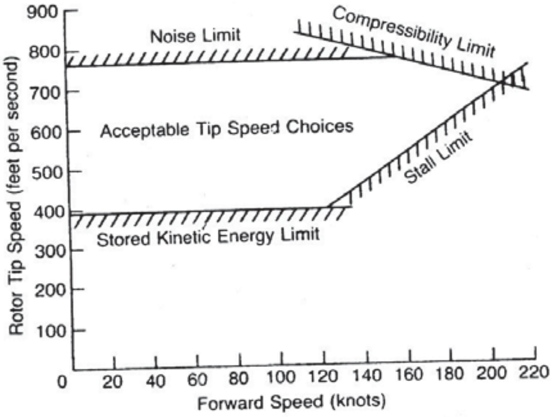

Figure 4 : *Tip speed design constraints [3]*

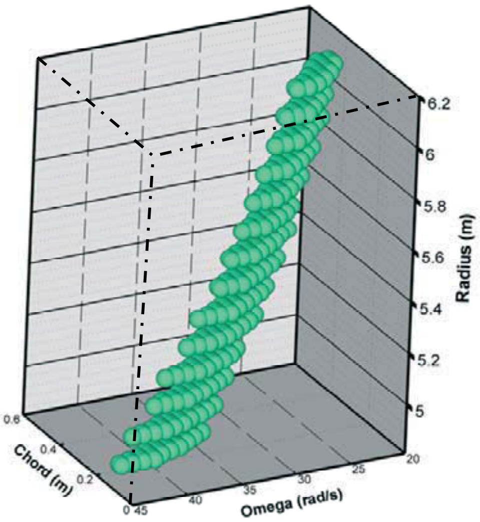

Figure 5 : *Available design parameter map.*

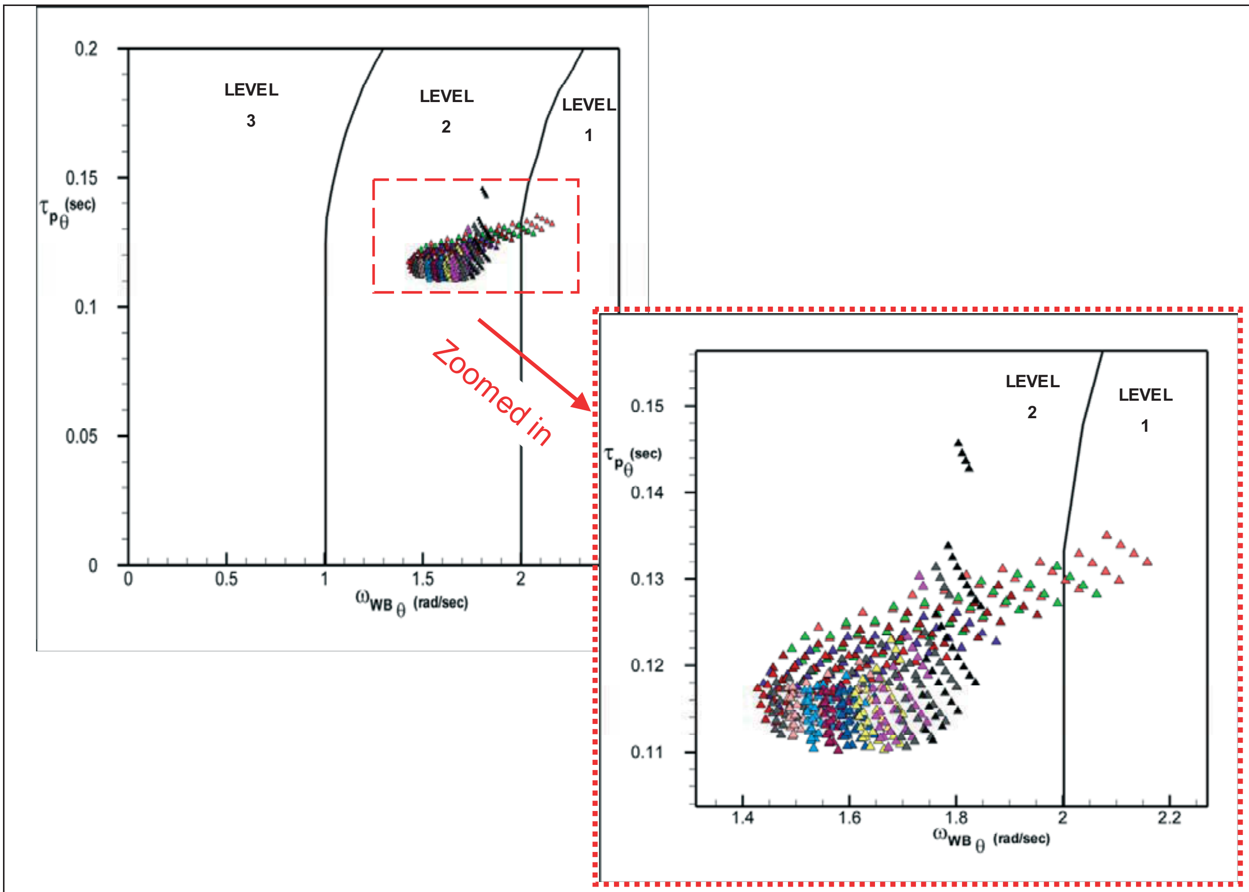

Figure 6 : *Bandwidth analysis results of whole design points.*

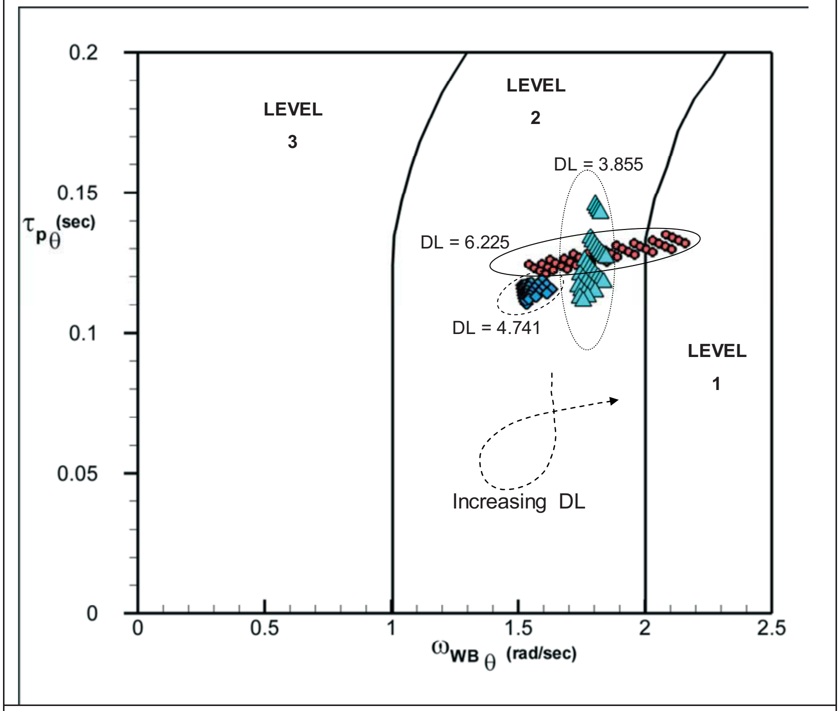

Figure 7 : *High (DL=6.225), moderate (DL=4.741) and low (DL=3.855) constant disc loading design maps and trend of disc loading maps.*

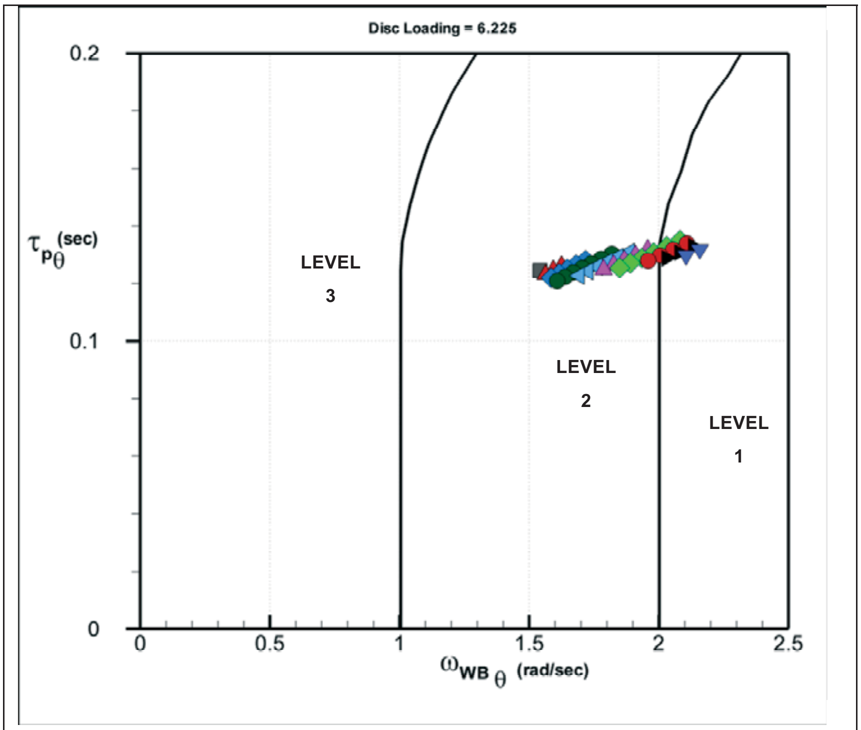

Figure 8 : *High disc loading (DL=6.225) design map.*

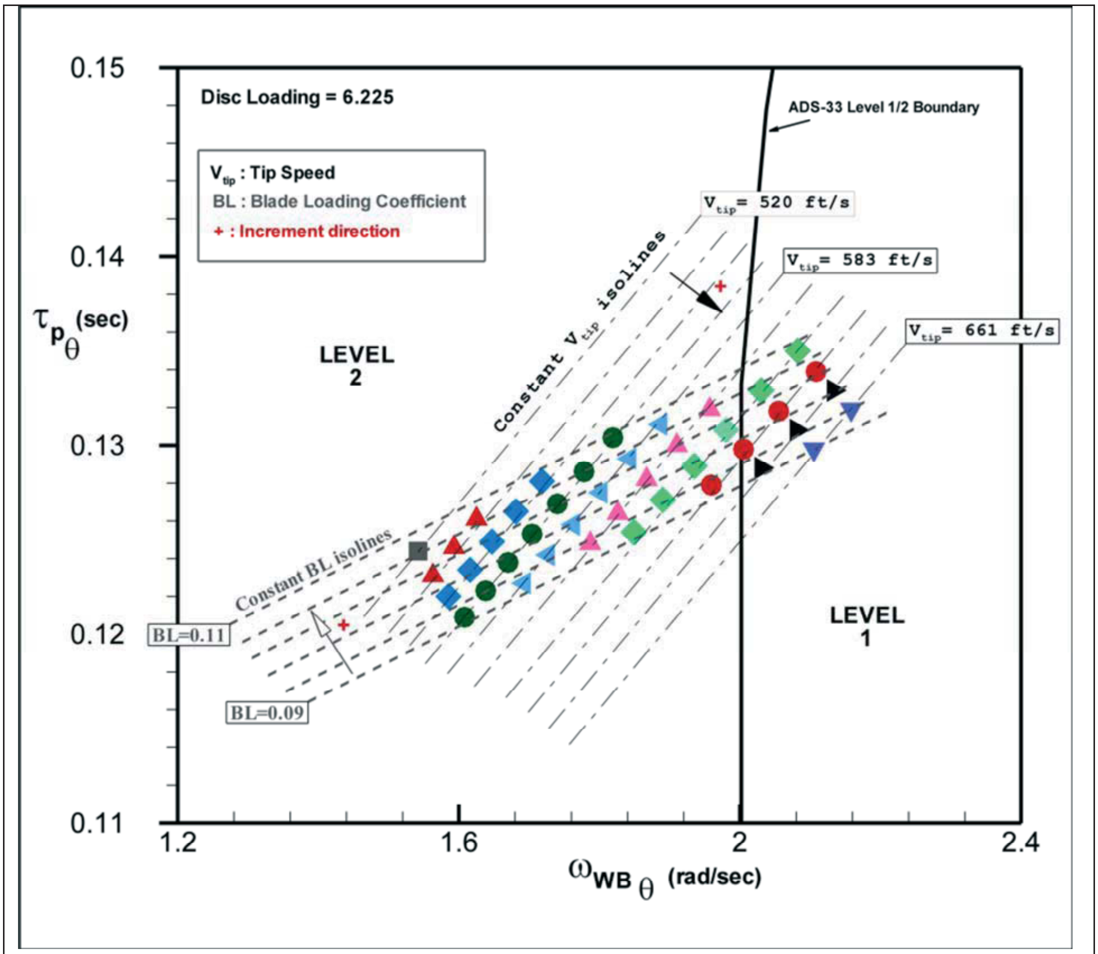

Figure 9 : *Zoomed high disc loading design map with tip speed and blade loading coefficient isolines.*

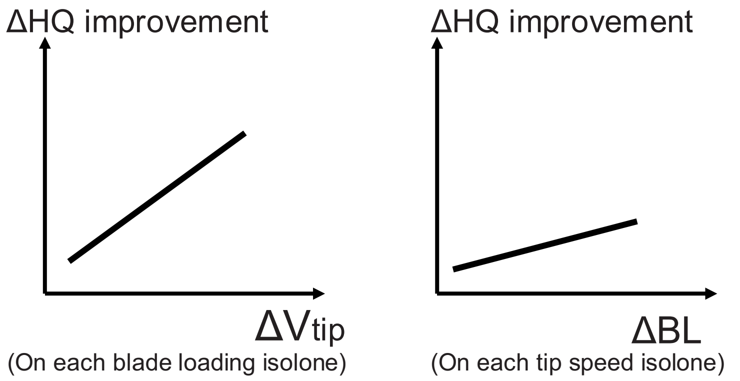

Figure 10 : *Representative graph of handling qualities leveling deviation with the varied design parameter for high disc loading case.*

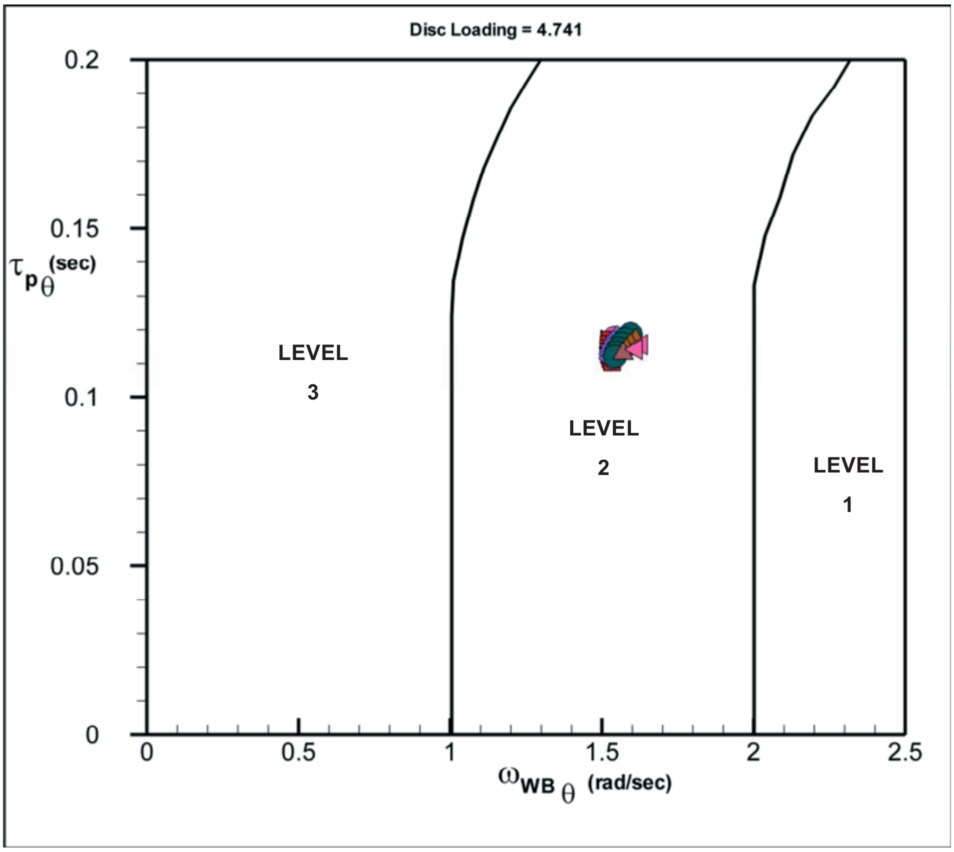

Figure 11 : *Moderate disc loading (DL=4.741) design map.*

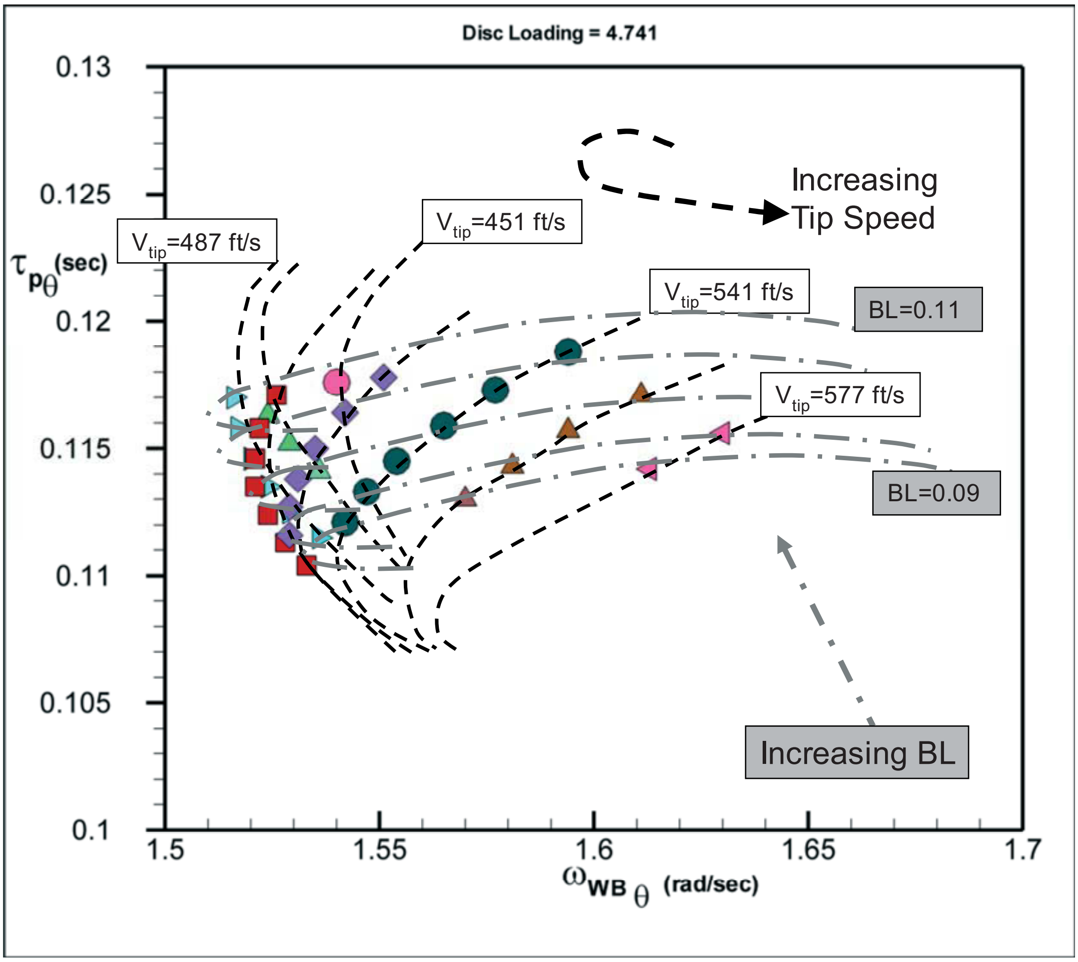

Figure 12 : *Zoomed moderate disc loading design map with tip speed and blade loading coefficient isolines.*

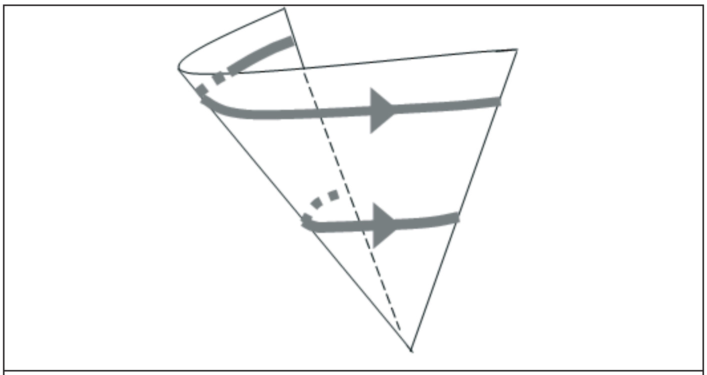

Figure 13 : *Sample representation of 3-D semi-cone translation during moderate disc loading case.*

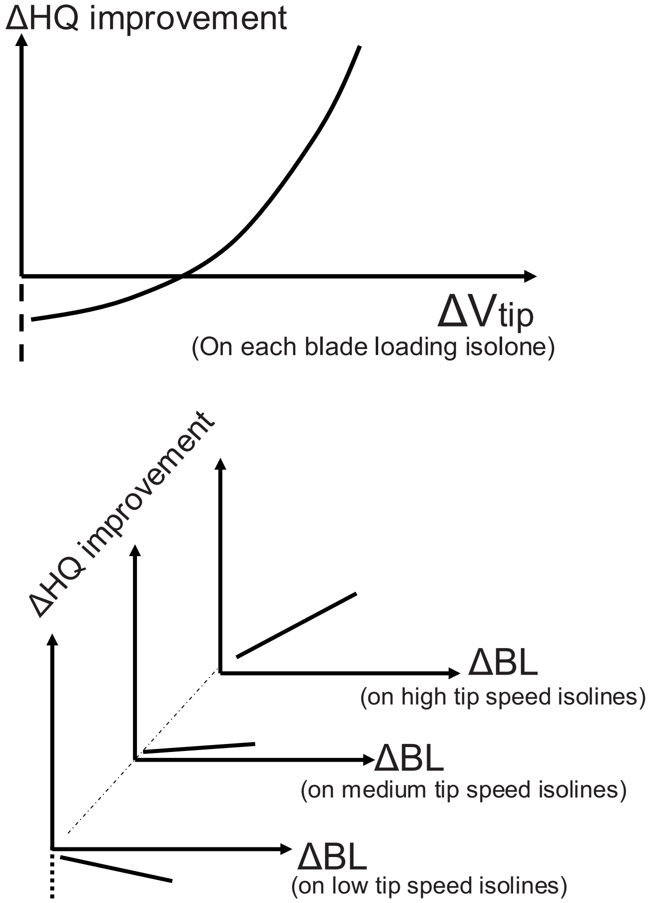

Figure 14 : *Representative graph of handling qualities leveling deviation with the varied design parameters for moderate disc loading case.*

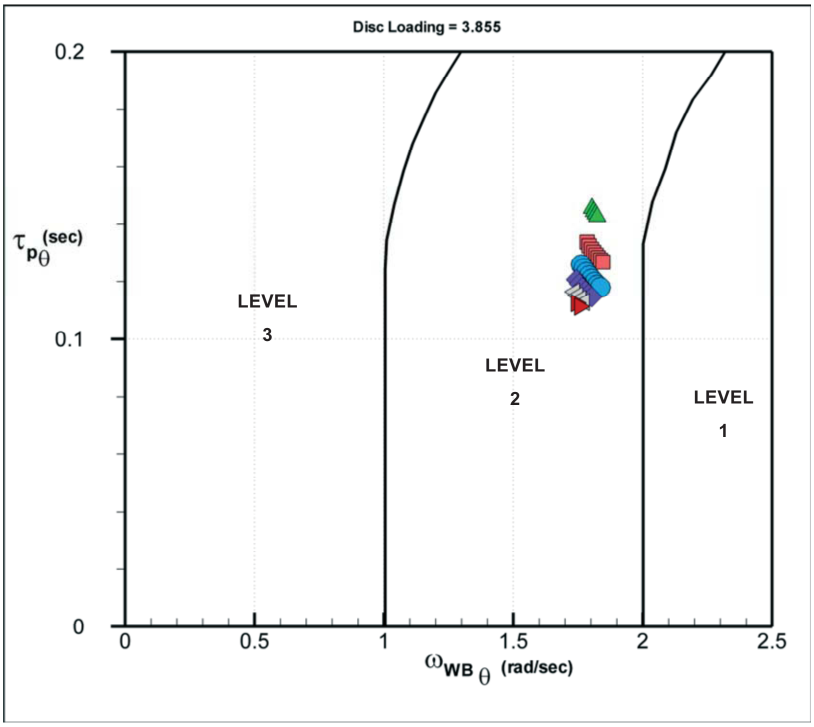

Figure 15 : *Low disc loading (DL=3.885) design map.*

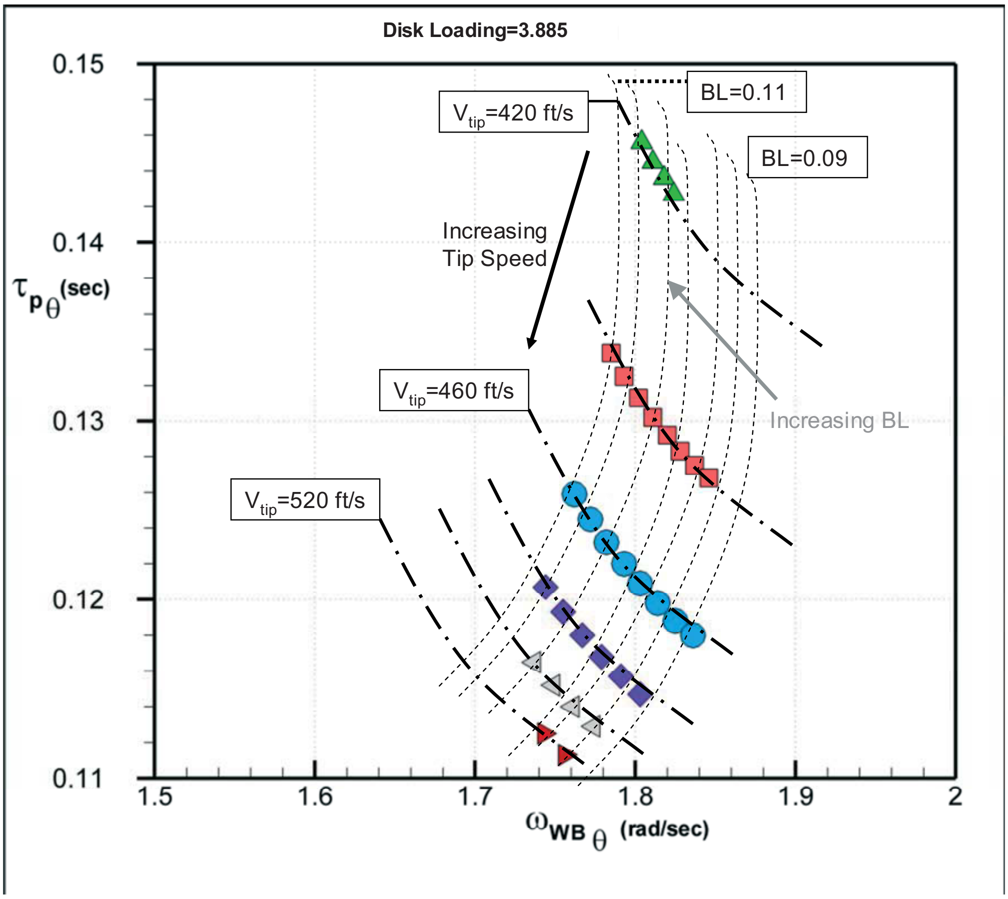

Figure 16 : *Zoomed low disc loading design map with tip speed and blade loading coefficient isolines.*

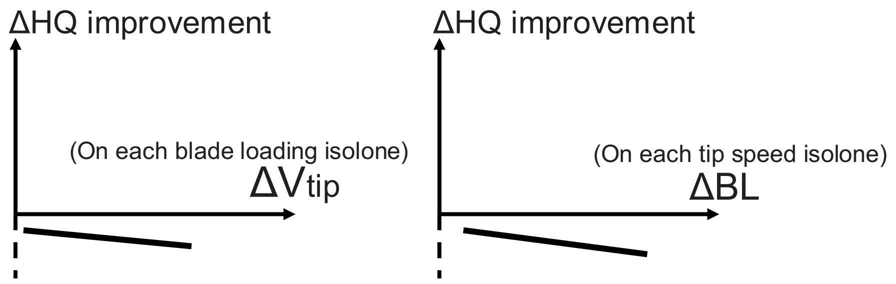

Figure 17 : *Representative graph of handling qualities leveling deviation with the varied design parameters for low disc loading case.*

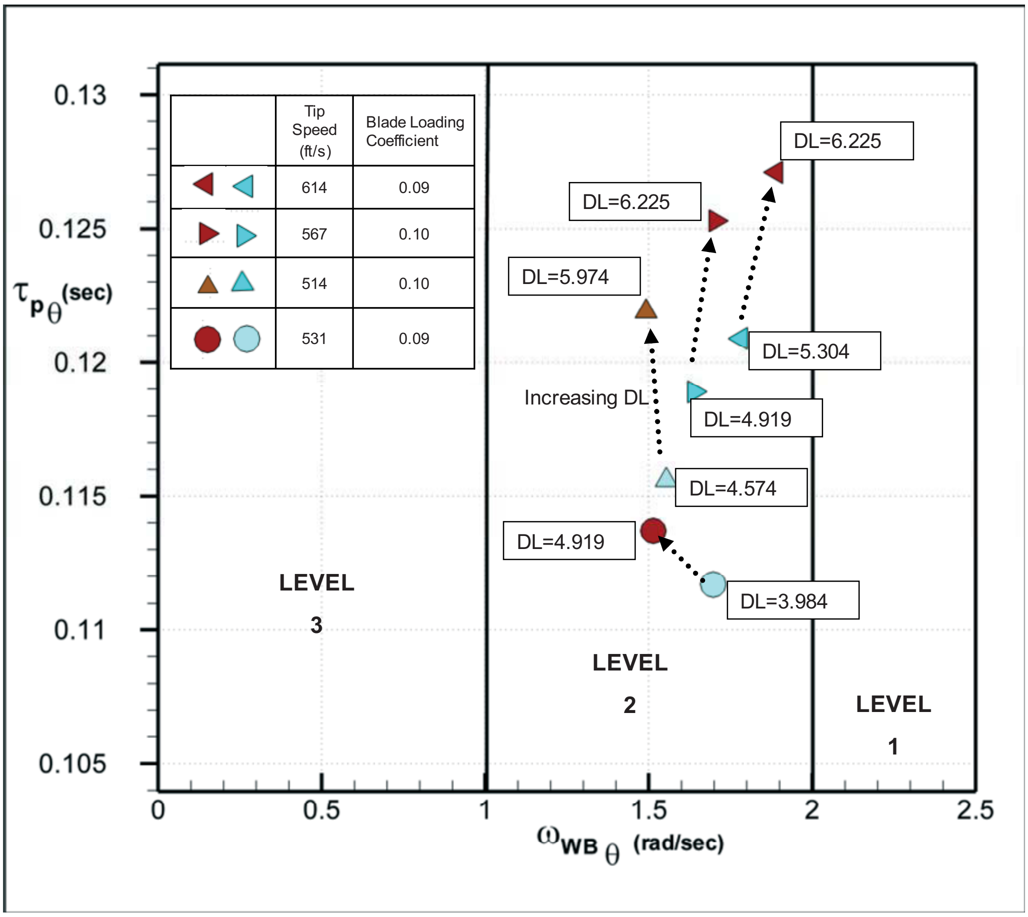

Figure 18 : *Deviation of disc loading for each constant tip speed and blade loading coefficient case.*

	Handling Quality			Effect of design parameter increment on HQ Enhancement	
Disc Loading	Design Interval	Minimum grade	Maximum grade	Tip Speed	Blade Loading Coefficient
High	Wide	Level 2	Level 1	⇧	⇩
Moderate	Narrowest	Level 2	Level 2	⇩ ⇧	⇩ ⇧
Low	Narrow	Level 2	Level 2	⇩	⇩

Table 1 : *Design parameter influence table*