Main Rotor Aeroacoustic Analysis & Validation with Test Data and Favorable Planform Design for Minimal Aerodynamic Noise

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Abstract

The main aim of this paper is to study the improvements or the deteriorations generated by blade planform modifications such as anhedral, taper, sweep, double sweep and their combinations on associated rotor characteristic which could not be straightforwardly evaluated with basic knowledge on aerodynamics, performance and aeroacoustic rule of thumbs. The physical mechanism behind the tradeoff between aeroacoustic, aerodynamic performance and rotor stall aspects is investigated and a better understanding for blade favorable planform shape design with low noise signature is developed. In this sense, blade planform modifications are performed on a base blade geometry and aeroacoustic, aerodynamic performance and stall onset characteristics are evaluated. Commercial tools such as Charm, PSU-WopWop and Camrad are utilized for comprehensive assessment~~s~~. Aeroacoustic and aerodynamic analyses are validated with an experimental rotor whirl tower tests and HART-II test data. Various blade planforms are evaluated and the trade-offs between less noisy blade planforms with stall onset, power requirements, lag-wise and torsional moments are studied. Eventually, the drawbacks encountered in aerodynamic performance and rotor stall while designing blade planform for improved acoustic characteristics are investigated.

Introduction

Considering helicopter total external noise, main and tail rotor aerodynamic noise, among engine, gearbox and transmission noises, are concluded as the most dominant contributor [[2], [3], [4], [5] and [6]]. Hence, although rotor aeroacoustic noise is a consequence of physical volume of the rotor blades and the forces acting on the air by the blades and cannot be totally eliminated or decreased below a physical boundary with today's technology [12], new design concepts such as noise minimal optimized blade planforms are encouraged by green rotorcraft programs and industry [1].

As being the principal aerodynamic noise source, amendment of rotor noise for especially certification imposed flight regimes increases public acceptance which seems to be a restricting argument for helicopter operations for the next decade [1], [6]. On the other hand, improvement in rotor noise may introduce deterioration in aerodynamic. Therefore seeking only a noise minimal blade planform design is evaluated as not consistent and sufficient with today's design needs. Therefore at design phase of noise minimal blade planforms, further evaluations performed with disciplines and issues such as aerodynamic~~,~~ performance and rotor stall assessment play a crucial role in developing favorable planform designs with low noise signature.

Basic knowledge on aerodynamic~~,~~ performance, flight mechanics and aeroacoustic theory rule of thumbs might be sufficient to evaluate effectiveness of basic planform and design modifications such as blade span, tip speed/rotational speed, blade number on design performance. However, evaluation of more advanced planform modifications such as anhedral, taper, sweep, double sweep and their combinations might not be straightforward.

In this study, a better understanding on improvements or deteriorations in aeroacoustics, aerodynamic performance and stall onset characteristics generated by each of the planform modifications (anhedral, taper, sweep, double sweep) and their combinations is aimed to be developed. The outcome of this study will be utilized to generate a base favorable noise minimal planform as starting point for further design studies. Additionally, this study will assist in generation of design objective function for planform optimization applications.

The aeroacoustic and aerodynamic analysis capability utilized in this study is validated with whirl tower tests with an experimental rotor and HART-II test data.

Then the parametric study on modification of helicopter main rotor planform geometry especially at the tip region is performed. Configurations are evaluated for noise levels, aerodynamic performance and stall onset. The effect of modifications in anhedral, taper, sweep on BVI noise, aerodynamic performance, and stall onset are investigated and favorable noise minimal planform designs are studied. the tradeoff between aerodynamic noise, aerodynamic performance and stall onset for various blade planforms are assessed.

Methodology

In order to develop a better understanding for this design problem, various blade planforms are evaluated for aeroacoustic, aerodynamic performance and rotor stall evaluations. Aerodynamic solutions are generated with CHARM which combines vortex and panel methods. Rotor performance and stall evaluations are performed with CAMRAD and aeroacoustic evaluations are performed with PSU-WOPWOP.. It is important to keep in mind that, the analysis cost, resolution and fidelity highly depends on the modeling capability tools used.

PSU-WOPWOP utilizes acoustic formulations to calculate rotor aerodynamic noise levels when blade azimuthal, radial and chord wise load distributions are supplied. The required information are generated with CHARM by modeling rotorcraft aerodynamics including full rotor-wake interactions enabling generating chord wise and radial aerodynamic load variations over the blade. CAMRAD, with free wake model, is utilized to determine rotor aerodynamic–performance, load fluctuations and stall onset characteristics. Rotor power requirements, control angles, rotor dynamic response and rotor load distributions are compared with each planform modification. Rotor load distributions are then integrated to determine blade lag wise and torsional moment variations over a blade revolution to assess stall onset and boundary characteristics for a specified blade planform.

Validation

For hover validation, whirl tower tests at various thrust levels, collective set angles and rotational speeds are conducted at TAI Whirl tower [6]. Experimental rotor parameters and analysis comparisons are presented with Fig. 1

Rotor Span	6 m
Nominal rotational speed	540 rpm
Tip Mach # Interval	0.5-0.8
Twist Angle (linear)	16°
Cone Angle	2°
Root-Cut Out	10%
Blade Number	2

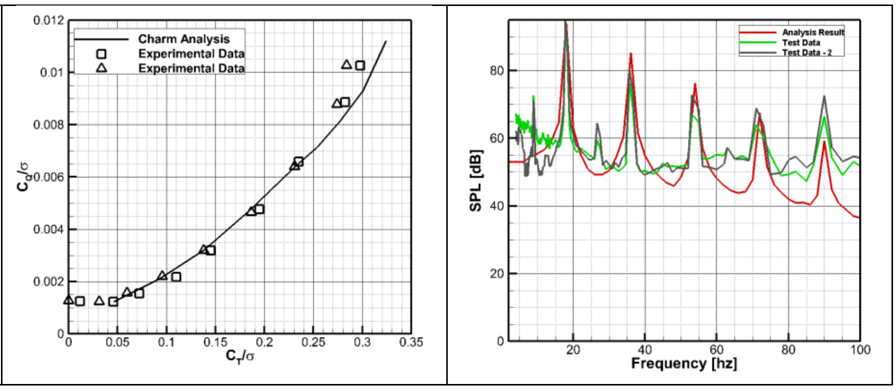

Fig. 1 Whirl tower test and validation

HART-II wind tunnel test case at which BVI noise is encountered is utilized to validate the aeroacoustic analysis ([7],[8]). The analysis is conducted for baseline rotor at μ=0.15, CT=0.0044 condition, trimmed for zero hub longitudinal and lateral moments with 5.3° shaft tilt. Observer is placed at the 11th test microphone location which is approximately at lateral 1.8 meters from hub at advancing side and 2.3 meters below the rotor. Time varying acoustic pressure, sound pressure frequency spectrum test and analysis comparison for the specified observer and noise contour plots below the rotor disk are depicted with Fig. 2.

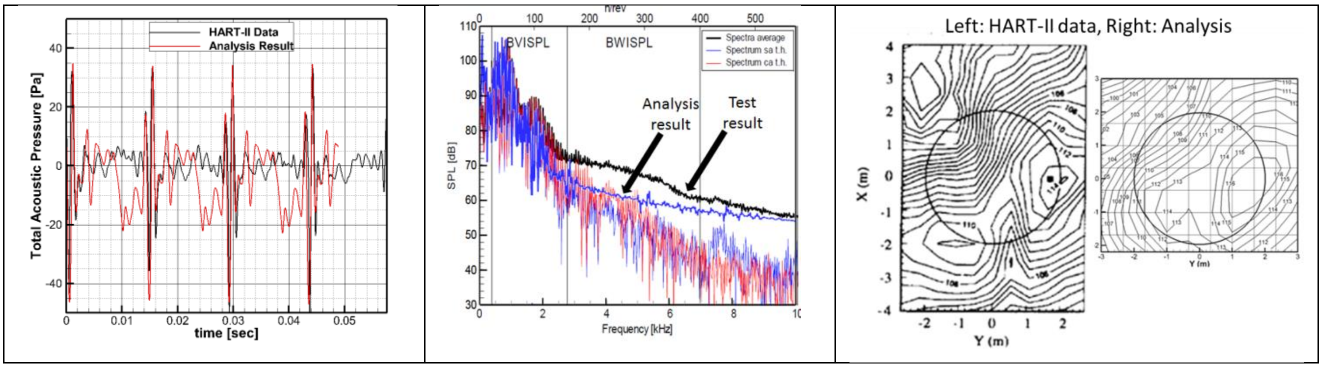

Fig. 2 HART-II – Analysis validation

Planform Evaluations

Various planforms are generated by modifications performed on a base geometry. Evaluations are performed in aeroacoustic, aerodynamic performance and rotor stall aspects and results are summarized. HART-II test model is selected as the baseline geometry and planform modifications are utilized on the planform. As test data of total noise levels of rectangular planform for the BVI case are present, noise evaluations and comparisons are performed for the same test condition. The baseline planform and modifications for which analyses are performed are listed with Table 1. Planform modifications evaluated with this study are visualized with Fig. 3.

Table 1 Baseline geometry (left), Planform modifications (right)

Rotor Span	4 m
Nominal rotational speed	1041 rpm
Twist Angle (linear)	-8°
Cone Angle	2.5°
Root-Cut Out	22%
Blade Number	4

Modification	**Variable Parameter**
Taper	Taper ratio: Ctip/Croot:0.8, Taper start: @0.9R
Sweep	Sweep angle: 12°, Sweep start: @0.9R
Double Sweep	Forward Sweep angle:-6° Backward Sweep angle 12° Sweep start: @0.75R
Anhedral	Anhedral angle:10° Anhedral start: @0.9R
Taper+Sweep	Taper ratio Ctip/Croot:0.8 Sweep angle 12°, Tip start: @0.9R
Taper+Sweep+Ahedral	Taper ratio Ctip/Croot:0.8, Sweep angle :12°, Anhedral angle 10° Tip start @0.9R
Taper+Double Sweep+Anhedral	Taper ratio : Ctip/Croot:0.8, Forward Sweep angle: -6° Backward Sweep angle: 12° Sweep start: @ 0.75R, Anhedral angle :10°, Tip start @0.9R @0.9R

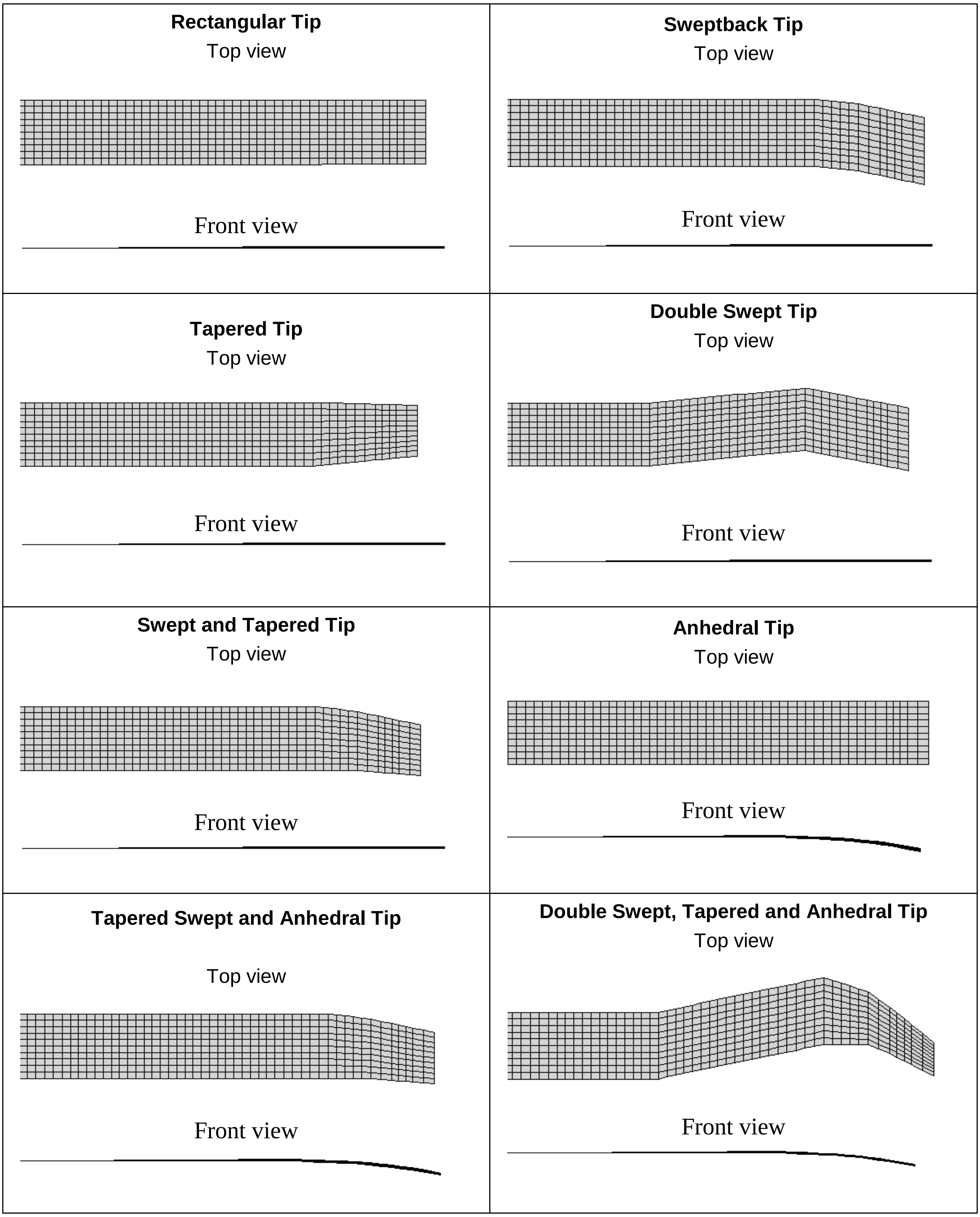

Fig. 3 Evaluated planform modifications

Noise analyses are conducted at μ=0.15, CT=0.0044, and the rotor is trimmed for zero hub longitudinal and lateral moments with 5.3° shaft tilt. Acoustic calculations are performed for an observer located at 1.8 lateral distances from the hub at advancing side and 2.3 meters below the rotor plane, where BVI noise is expected to be dominant. Aerodynamic analyses are performed with CHARM at various forward level flight conditions for same thrust levels, total thrust to total power ratios are compared. Power curves are generated with CAMRAD at same CT/σ up to 0.4 advance ratio and power requirements are compared. To assess the variation in flight quality with increasing flight speed at associated CT/σ values, stall onset analyses are performed. Stall onset boundary is defined as a notable change in the rotor torque which results in a rapid decrease in flight comfort/quality [9]. Utilizing CAMRAD stall onset boundary for each of the configurations are generated and compared.

Acoustic Evaluation

Acoustic pressure time variations are determined for each configuration at the observer location. FFT analyses are performed and total sound pressure levels for the first 200 harmonics are integrated to determine BVISPL values for each configuration. The percent of BVI noise improvements depicted with Fig. 4 over the baseline configuration are investigated with SPL values in logarithmic scale whereas the aerodynamic efficiency are investigated as percent improvement on baseline configuration.

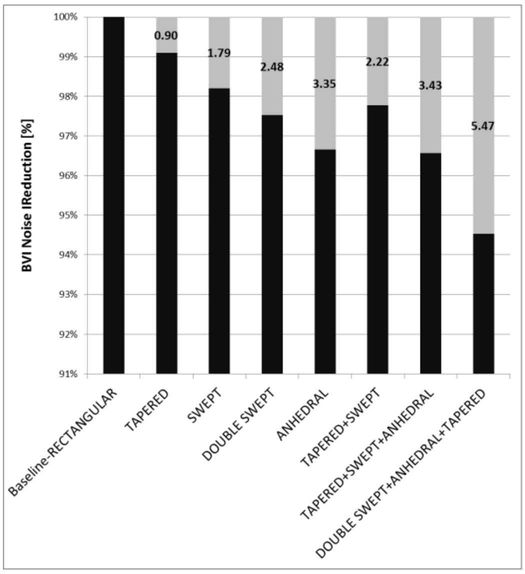

Fig. 4 BVI Noise improvements

It is observed that each of the tip modification has improving effect on BVI noise within a range of %1-%5.5. Whereas “TSA” (Tapered+Swept+Anhedral) configuration and “DSAT” (Double Swept+Anhedral+Tapered) configuration are observed to have highest improvements on BVI noise for this particular analysis case.

Aerodynamic Performance Evaluation

To evaluate aerodynamic efficiency improvements, efficiency metric is defined as total thrust to total torque. CHARM is utilized to perform level forward flight analyses up to 0.4 advance ratio. In order to have comparable results for different planforms, analyses are performed at constant and same C_T/σ values. Aerodynamic efficiency improvements over the baseline rectangular geometry are presented with Fig. 5 for each of the configuration.

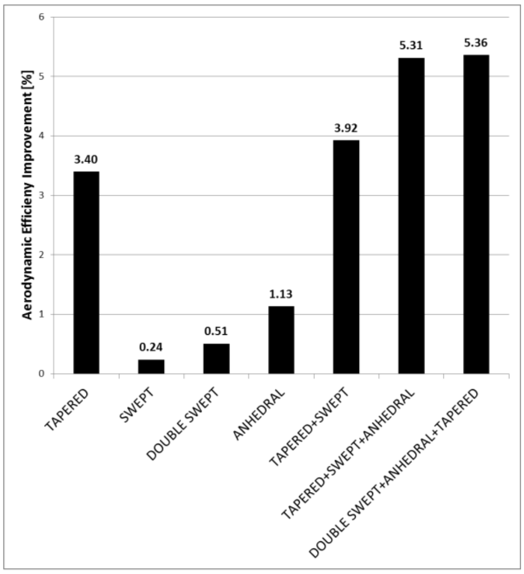

Fig. 5 Aerodynamic efficiency improvements

Each of the tip modification has improving effect on aerodynamic efficiency metric compared to the baseline configuration within a range of %1-%5.5. Whereas “TSA” (Tapered+Swept+Anhedral) configuration and “DSAT” (Double Swept+Anhedral+Tapered) configuration are observed to have highest improvements aerodynamic performance for this particular analysis case.

Power required variation with increasing forward speeds at three C_T/σ values are determined for each of the configuration and compared. Three C_T/σ cases represent lightly loaded, medium loaded and highly loaded conditions. Solidity is calculated with equivalent chord lengths and thrust coefficient values are manipulated giving same C_T/σ for all configurations in order to generate comparable conditions. Analyses are performed with CAMRAD and CHARM, free wake models using wind tunnel trim option with thrust, forward force and lateral flapping angle as trim targets. Total power required values for three loading scenarios (lightly, moderate, highly loaded) are normalized with baseline geometry and an improvement metric is developed representing all flight speeds up to 0.4 advance ratio.

Power required improvements for each of the modifications over the baseline configuration are presented with Fig. 6.

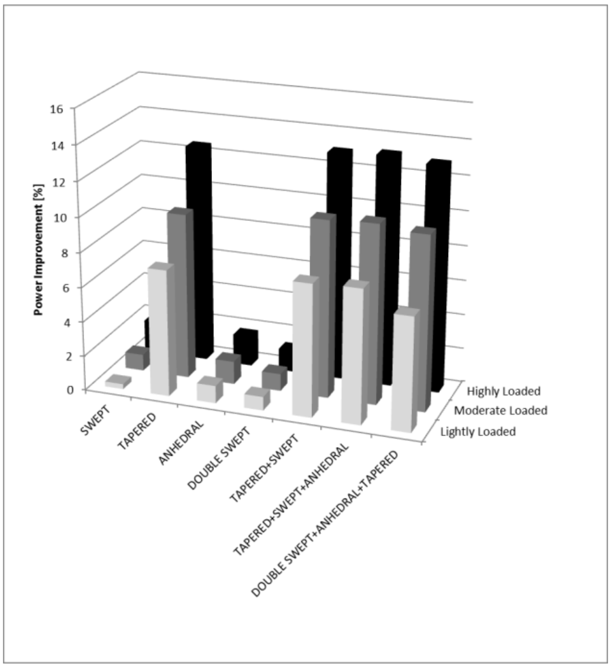

Fig. 6 Power required improvements

It is observed that, taper is the main contributor to power required improvements while other modifications such as sweep, anhedral and double sweep have relatively minor contribution to power requirements.

Stall Onset Evaluation

For 0.3 advance ratio level forward flight condition at same C_T/σ loading, torsional moment variation in one revolution is studied for each of the configurations. Peak to peak variation of the torsional moment values are normalized with baseline configuration to determine improvements or deteriorations. Results are presented with Fig. 7.

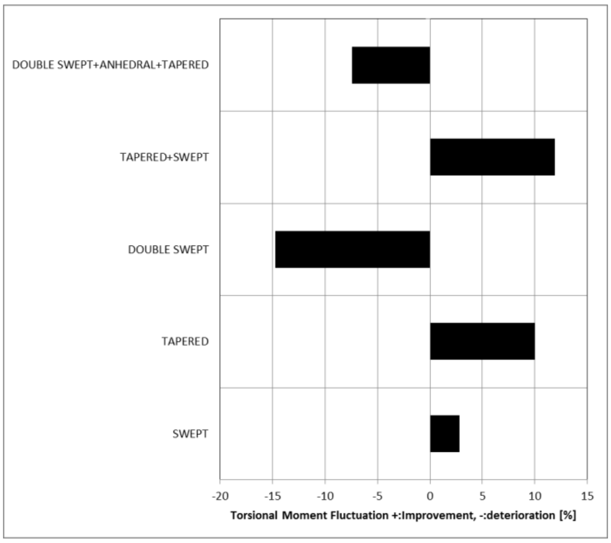

Fig. 7 Torsional Moment Fluctuation Improvement or Deterioration

Double sweep configuration displays an increase in torsional moment variation while other modifications such as sweep, taper and their combinations generates improvements by decreasing the torsional moment fluctuations.

Configurations are evaluated with stall onset characteristics. Although rotor stall could not easily be captured and has not a specific indication, there are various methodologies for estimating stall onset boundary in the literature [9], [10]. In this study, stall onset boundary is defined as a notable change in the blade torsional moment fluctuations in one revolution which results in a rapid decrease in flight comfort/quality [9]. Results are presented with Fig. 8

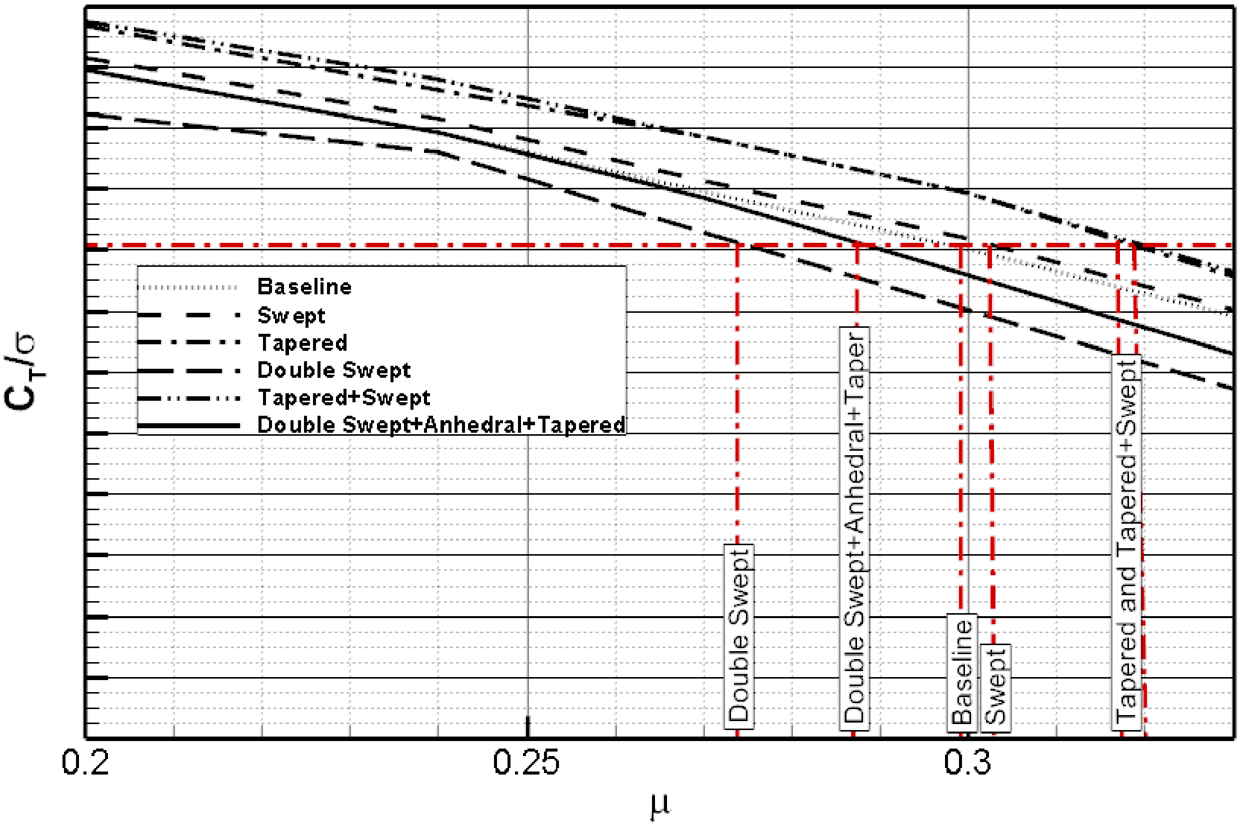

Fig. 8 Stall onset evaluation

When torsional moment fluctuations considered, double sweep configurations display deterioration in torsional peak to peak variation which decreases stall onset performance.

Acoustic Evaluation Revizited

For further evaluation, total acoustic pressure variation with time for Baseline, “TSA” and “DSAT” configurations are plotted and presented with Fig. 9.

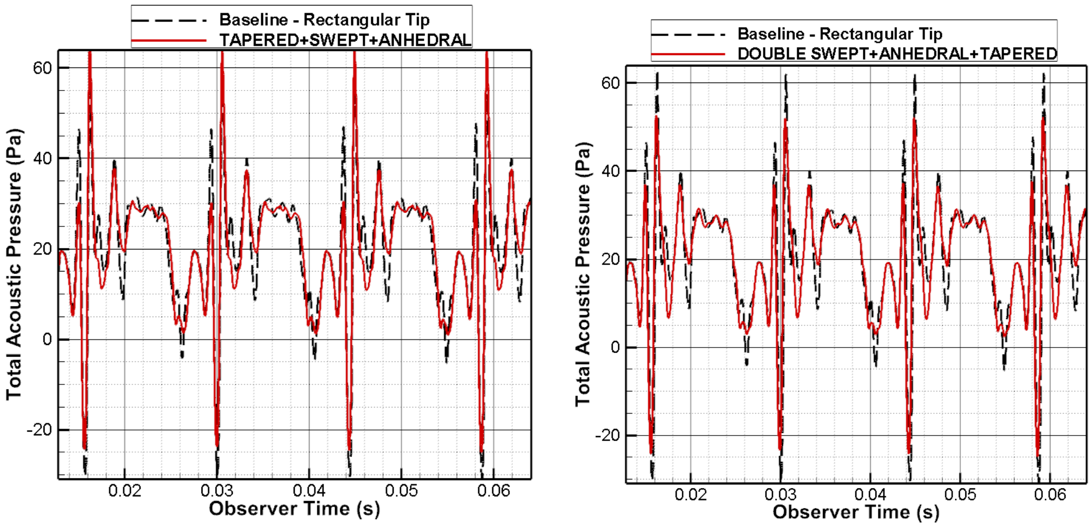

Fig. 9 Acoustic Pressure Time Variation

Similarly, sound pressure levels (dB) contour below rotor disk for specified configurations are depicted with Fig. 10.

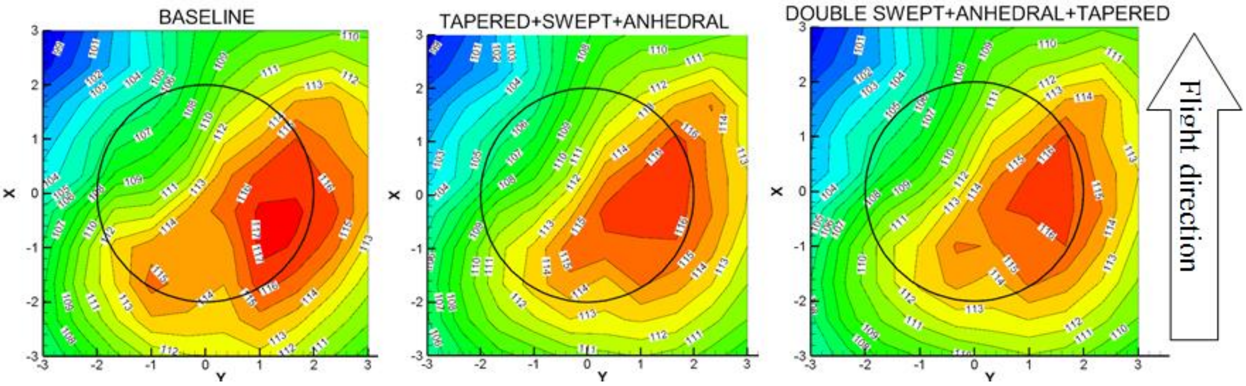

Fig. 10 Sound Pressure Level Contours Below Rotor Disc

Three pressure peaks are generated at each blade passage and dominate the total sound levels at this particular BVI noise case. The combination of taper, sweep and anhedral at tip region decreases the absolute pressure values for the first two peaks without changing the third peak. Whereas, the addition of the second sweep angle on the same configuration, furthermore decreases the absolute pressure value of the third peak, resulting an additional %2 decrease in BVI noise levels. Similar conclusion is made with the SPL contour comparisons. Combination of taper, sweep and anhedral at tip region decreases the concentrated noise lobe at rotor advancing side below the disk both at magnitude and size. Addition of the second sweep angle on the same configuration furthermore decreases the concentrated noise lobe at rotor advancing side below the disk both at magnitude and size.

Conclusion

Today’s certification standards for maximum noise levels, clean sky considerations [11] and effort to decrease manufacturing and maintaining costs impose multi-disciplinary optimal rotor designs. This requires noise minimal, aerodynamically efficient blade planforms with lower power requirements and load fluctuations resulting in higher stall onset boundaries. Consequently, it is concluded that for new designs, advanced planform geometries with taper, sweep and anhedral combinations are decisive.

In this study, a better understanding on favorable noise minimal blade planform design is developed. Improvements or deteriorations in aeroacoustics, aerodynamic performance and stall onset characteristics generated by each of the planform modifications (anhedral, taper, sweep, double sweep) and their combinations are studied and results are presented. It is concluded that each blade planform modification influences performance characteristics at each discipline differently. For example, double swept+anhedral+tapered blade planform configuration is observed to have highest noise improvement over the baseline geometry however when assessed in terms of torsional moment fluctuation, is observed to have highest peak-to-peak variation. Because of this, design objective function weights in a multi-disciplinary optimization process are required to be defined properly for a meaningful optimization result.

This multi-objective understanding will asist for further and higher fidelity design, analysis and trade-off evaluations. The outcome of this study will be utilized to generate a base favorable noise minimal planform as starting point for design optimization studies and to generate design objective function and associated weights.

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