

DYNAMIC LOADS REDUCTION OF LIFTING PROPELLERS THROUGH GEOMETRIC MODIFICATION

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Abstract

Innovative, low-emission electrical vertical take-off and landing (eVTOL) concepts require the use of highly efficient lifting propellers due to the high power demand during hover. In these eVTOL systems, the operating conditions vary between hover and forward flight. The propellers are used to generate lift during forward flight, introducing dynamic loads caused by cross-flow and the resulting unsteady inflow conditions across the advancing and retreating blades. The conventional structural design processes for general aviation propellers such severe dynamic loads are not considered. Applying these conventional methods would lead to excessively heavy propellers, as the dynamic loads—causing severe vibrations and bearing moments—would need to be fully tolerated. Within the NERO (Novel Emission Reduction through Optimisation) project, the influence of geometrically modified propellers on the resulting dynamic loads under oblique inflow conditions is investigated. This paper presents a transient aerodynamic-structural coupled method to calculate the dynamic loads on propellers subjected to oblique inflow using a time-marching approach. A Blade Element Theory (BET) coupled with a linear inflow model is used to compute the unsteady aerodynamic forces, while structural loads and deformations are determined using a one-dimensional beam theory. In the chosen parameter space, the most effective reduction in dynamic loads and amplitude is achieved using an s-shaped forward-swept propeller. The results show a dependency on the operating conditions. Additionally, the application of a pre-cone angle counteracts aerodynamic forces and leads to a significant reduction in the time-averaged bending moments. The presented method enables the evaluation and detailed analysis of the complex coupled behavior of propellers under oblique inflow conditions. Furthermore, a case study on the eMagic One is conducted to assess the potential for structural load relief under various flight conditions, taking into account the parameters of a recently developed eVTOL aircraft.

Keywords

Propeller; Sweep; eVTOL; Dynamic Loads; Optimisation; Aero-structural interactions; Transient Simulation

List of symbols

B	Bernstein polynomial
C	Damping matrix
F	Load vector
K^G	Geometric stiffening matrix
K^L	Linear stiffness matrix
K^{SP}	Spin softening matrix
M	Mass matrix
N	Maximum DoF of the Bernstein polynomial
r	Relative position along the blade radius
u	Nodal deformations
v_∞	Flight velocity $[\frac{m}{s}]$
w	Sectional air velocity $[\frac{m}{s}]$
Ω	rotational speed $[\frac{1}{min}]$
Ψ	Azimuth blade position $[\circ]$
α	Parameter of the HHT- α algorithm
α_{eff}	Effective Angle of Attack $[\circ]$
θ	Torsional deformation $[\circ]$

Indices

∞	Infinity condition
i	Index of radial blade section

Exponents

e	Sectional coordinate sytem
p	Blade coordinate system
R	Rayleigh dampiong
G	Geometric
L	Linear
SP	Spin softening

Abbreviations

AoA	Angle of Attack
BET	Blade Element Theory
DoF	Degree of Freedom
eAoA	Effective Angle of Attack
eVTOL	Electric Vertical Take-Off and Landing
FEM	Finite Element Method
HHT- α	Hilber-Hughes-Taylor- α
NERO	Novel Emission Reduction through Optimisation
RANS	Reynolds-Averaged Navier-Stokes

1. INTRODUCTION

Recent developments for electrical vertical take-off and landing aircraft (eVTOL) use propeller driven distributed propulsion systems for both, hovering and cruise flight.

Manufacturers developed different configurations to fulfil the propulsion requirements. Tilt-propellers are able to switch from hover mode to cruise mode by in-flight tilting as implemented by Joby Aviation and Vertical Aerospace [1, 2]. Other designs use different systems for thrust and lift as realised by Autoflight or MK Technology [3, 4]. The eMagic One by MK Technology is shown in Fig. 1 with its distributed propulsion system. Avilus developed a military transport drone Grille [5]. The flight control system of the Grille is similar to that used in conventional drone applications, where speed regulation controls the lifting propellers and thus the flight manoeuvres. Yan et al. define two categories for eVTOL applications where propeller systems are used for both, hover and cruise [6].

- **Lift and cruise propulsion systems:** Some propellers are primarily used for thrust, while others are primarily used for lift. This simplifies the control strategy but increases the aircraft's overall weight. Additionally, dynamic loads are elevated because lifting propellers are exposed to oblique inflow conditions during forward flight.
- **Tilt-rotor systems:** These can transition between VTOL and cruise modes by mechanically tilting the rotors. While effective, the required tilt mechanisms increase overall system weight. During the tilt process, varying cross-flow angles affect aerodynamic behaviour and must be considered in the design phase. Additionally, these systems require sophisticated aerodynamic and flight dynamic control.

The first aspect of the research project NERO is the improvement of hover efficiency and reduction of noise emissions for eVTOL propeller applications [7]. The chord length and twist distribution is modified, which results in increased efficiency and a reduced noise emissions [8]. A detailed noise emission analysis and experimental data resulting from the project are shown by Bergmann [9].

The second aspect of the research project NERO is to analyse the structural dynamic behaviour of fixed propellers under oblique inflow conditions. A lifting propeller which is used for hovering and forward flight is affected by vibrations. These vibrations or dynamic loads result from the inflow conditions. The changing conditions are caused by the flight inclination angle and flight velocity v_∞ . The varying inflow excites the structure, leading to fatigue damage or exceeding the strength limit of the material. During a single revolution of a blade the total inflow velocity at a blade section w changes over the azimuth angle Ψ . The side where w increases due to the circular velocity Ω is called the advancing side; the side where Ω reduces the sectional velocity w is known as the retreating side. The changing magnitude of the total velocity component results in dynamic loads at a frequency excitation similar to the rotational speed. Thus the magnitude of dynamic loads depends on the flight velocity v_∞ , the rotational speed Ω , and the inclination angle of the aircraft. Experiments with steerable thrusters of ships show an increase of the structural loading with a factor of three compared to the axial flow condition [10]. Furthermore, the crash of the novel eVTOL VA-1X by Vertical Aerospace in 2022 is attributed to imbalanced effects during forward flight leading to the release of a propeller blade and thus the destruction of the aircraft.

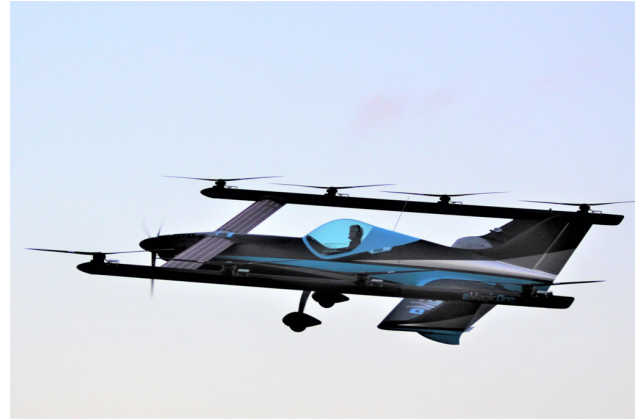


FIG 1. eVTOL eMagic One by MK Technology [4]

PropCODE (Propeller Comprehensive Optimisation and Design Environment) is an in-house software tool by FH Aachen. The coupled solver is applied to simulate aerodynamic-structural interactions of propellers in the time domain [11, 12]. Within this study, PropCODE is utilised to analyse the influence of propeller sweep on the dynamic loads of fixed-pitch propellers under oblique inflow conditions. The results from the simulation are evaluated and shown within this paper.

Modern transonic civil aviation aircraft have swept wings to reduce compressibility effects. Swept wings have less compressibility issues than unswept wings, which leads to a drag reduction in high speed operations. The sweep form of a wing also influences stability and handling control, as discussed in [13]. The application of a swept geometry is transferred from wings to propellers. Swept propellers are affected by two different aspects: First, numerical and experimental data show a decrease in the overall noise emissions of swept propellers, primarily due to reduced broadband noise emissions [14]. Hanson states that swept propeller are able to reduce the total noise emissions [15]. Experiments on forward-swept propellers performed by Neuwerth demonstrate increased efficiency and reduced noise emissions; but this depends on the exact sweep form [16]. Second, swept propeller geometries can lead to structural interactions. The shape of a swept propeller creates tangential offsets between different blade sections that act as lever arms, generating a torsional moment which is known as torsional-bending coupling. When designing swept propeller geometries, it is necessary to consider torsion-bending coupling in relation to the stiffness distribution and strength since torsional loads increase [11]. The torsional-bending coupling of swept propellers is used to influence the overall propeller performance [17, 18]. The effect of torsional-bending coupling is analysed and used for dynamic loads reduction within the analysis of swept propellers under oblique inflow conditions.

2. METHODOLOGY

The analysis of structural effects related to the aerodynamic of swept propeller geometries requires an aerodynamic-structural coupled solver. PropCODE is an in-house tool for the comprehensive analysis of propellers. The tool includes two design processes for propellers. First, a propeller design method for a single operating point according to the minimum induced loss (MIL) condition [19]; and second, a genetic algorithm which considers a complete flight mission where the chord length and twist distribution is optimised

considering efficiency and noise emissions. A steady solver calculates the aerodynamic performance of a propeller with BET, extended by a linear inflow model. The aerodynamic module has been validated against high-fidelity CFD RANS methods in Ref. [20]. An 1D-FEM solver calculates the structural loads that allocates material properties to arbitrary layups of composite material. The composite material data of the manufacturer is used for the calculation of the stiffness and mass distributions. The structural module has been validated against advanced commercial FE methods, as detailed shown in [21]. The aeroelastic of the propeller in a steady state is computed and evaluated using closely coupled methods. Deformations and loads occurring at a defined steady operating point can be evaluated in detail, and the difference between the rigid and elastic cases are analysed.

The evaluation of the structural and aerodynamic performance under oblique inflow conditions requires a coupled transient quasi-steady solver. The solver methods under discussion originate from the steady methods. The hht- α time integration scheme is implemented in PropCODE. The HHT- α solver is a one-step implicit method for solving transient problems [22].

2.1. Structural Model

The structural model takes into account both the behaviour of anisotropic materials and the arbitrary cross-sectional planforms of hollow structures. The 1-DoF element solver comprises radial distributed sections. Fig. 2 shows the built blade section alongside the reference coordinate system.

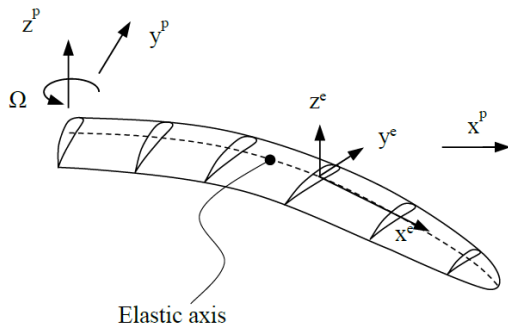


FIG 2. Degrees of Freedom for 1D-FEM method [23]

The equation of motion as a second order differential equation is defined in Eq. 1.

$$(1) \quad M \cdot \ddot{u} + C \cdot \dot{u} + K \cdot u = F$$

For the purposes of this analysis, Eq. 1 becomes time-dependent. Due to the oblique inflow conditions and the aerodynamic coupling, the external forces depend further on the structural deformations, e.g. the changing angle of attack. Rotordynamic effects are taken into account with the gyroscopic matrix. The stress stiffening effect due to the system's rotation is also considered here. This results in the governing equation of motion, as described in reference [11].

$$(2) \quad \begin{aligned} & M \cdot \ddot{u} + (C^R + G(t)) \cdot \dot{u} \\ & + (K^L + K^G(F) + K^{SP}(t)) \cdot u \\ & = F(u, \dot{u}, \ddot{u}, t) \end{aligned}$$

The mass matrix is represented by M , the Rayleigh damping matrix by C^R and the gyroscopic matrix by G . The stiff-

ness component K^L represents the linear stiffness of the static blade structure. To take geometric stiffening and spin softening into account, the matrices K^G and K^{SP} are considered. External forces in Eq. 3 result from the aerodynamic model with the aerodynamic forces F_{aero} and the centrifugal mass forces F_{mass} .

$$(3) \quad F(u, \dot{u}, \ddot{u}, t) = F_{aero}(u, \dot{u}, \ddot{u}, t) + F_{mass}(t)$$

2.2. Aerodynamic Model

The aerodynamic model is based on an extended Blade Element Theory (BET), which incorporates principles of momentum theory. The detailed methodology and validation process are described in the corresponding reference by the developers of PropCODE [20]. The propeller geometry is divided into two-dimensional cross sections. Each airfoil section is analysed using its specific lift, drag, and moment coefficients, which are calculated with XFOIL. The Mach number and Reynolds number dependencies are thereby taken into account. Prandtl's root and tip loss correction [24] as well as a 3D stall correction method [25] extends the 2D airfoil data to a finite blade. In 1935 Busemann proposed that only the velocity component perpendicular to the leading edge contributes effectively. An inflow correction based on Busemann's theory is implemented to account for aerodynamic effects resulting from the swept geometry of the propeller [26, 27].

2.3. Applied calculation scheme

The definition of the aerodynamic and structural sections can differ from each other for mesh size adaptations. The aerodynamic sections need to be coupled to the structural sections. The sectional parameters such as forces etc. are transferred by an orthogonal projection to the other coordinate system accordingly by the interpolation method of a modified akima spline [28]. The structural reference system is defined by the elastic axis, while the aerodynamic reference systems is defined by the quarter-chord line.

The applied calculation scheme is implemented according to the hht- α algorithm [22]. The detailed implementation into PropCODE is shown in [11]. Eq. 4 shows the time step development according to Eq. 2.

$$(4) \quad \begin{aligned} & M\ddot{u}_{n+1} + (1 + \alpha)\dot{u}_{n+1} - \alpha C\dot{u} + (1 + \alpha)Ku_{n+1} - \alpha Ku_n \\ & = F_{n+1} \end{aligned}$$

With the main parameter α for stability and numerical dissipation. For the illustrated simulations of this paper the value is set to $\alpha = -0.1$.

$$(5) \quad -\frac{1}{3} \leq \alpha \leq 0$$

3. DERIVATION OF PROPELLER GEOMETRY

The reference unswept propeller results from an multidisciplinary optimisation, where the efficiency of high aspect ratio lifting propellers is increased by a modification of the chord length and twist distribution, while the noise emissions are minimised. Fig. 3 shows the geometric parameters of the resulting reference propeller. The original propeller, which was optimised regarding efficiency and noise emissions, is the H26F LFL-225m-2B of Helix Carbon GmbH [29]. The H26F is a high aspect ratio lifting propeller

with a diameter of $2.25m$ designed for modern eVTOL application with a focus on hover efficiency.

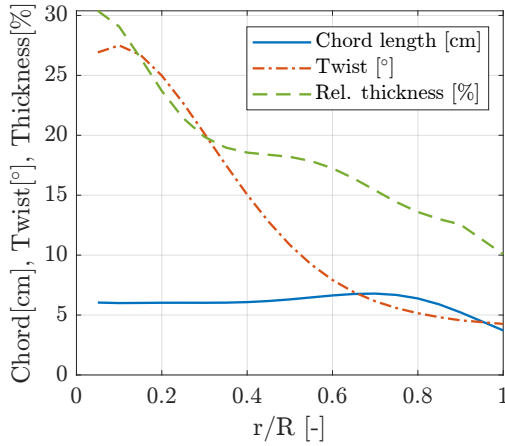


FIG 3. Constant geometric parameter distribution of unswept and swept propeller

The diameter is kept at a constant value of $2.25m$, similar to the H26F propeller. For the design the airfoil from the 4th digit NACA serie '64' with decreasing relative thickness is used as described in Tab. 1. Tab. 1 further shows the thrust and power consumption at the design point at $1800min^{-1}$, which is optimised for hover flight.

Design RPM	$1800 \frac{1}{min}$
Design thrust	905N
Power (1800RPM)	11.13kWh
Diameter	2.25m
Root chord	0.058m
Taper ratio	0.48
Root twist	11.6°
Tip twist	2.3°
Airfoil	NACA 6426 to 6412

TAB 1. Reference propeller parameters

Fig. 4 shows the mass and stiffness distribution of the unswept reference propeller. With increasing radius and decreasing chord length the mass fraction decreases. Further the bending stiffness in form of EI_{yy} behaves accordingly. The middle section is stiffened with high-modulus fibres in $\pm 45^\circ$ direction to increase torsional stiffness and account for the increased load due to torsional-bending coupling. The ply starting position results in a relative decreased root bending stiffness.

According to Möhren [11], the bending stiffness of lifting propellers with large diameters is primarily driven by centrifugal stiffening rather than elastic material stiffness. The centrifugal forces increase with larger diameter. Therefore, translational deflections in bending directions have a larger counteracting effect on aerodynamic forces. Bending deformations relative to the diameter are reduced, thus decreasing dynamic amplitude in bending direction. However, the mean root bending loads increase with large diameters due to increased lever arms. The mean root bending moments are also effected by a pre-cone angle, compare Chapter. 3.2.

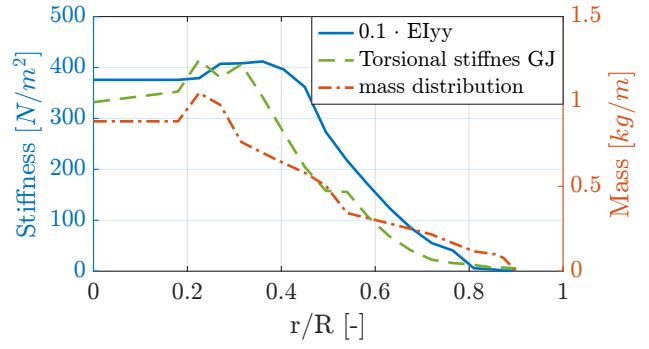


FIG 4. Mass and stiffness distribution for the swept propeller geometry

3.1. Sweep Forms

Three different sweep forms have been analysed in a previous study, a s-shape, a quarter cosine wave and a tip modification [30]. The geometry's shape functions are defined by the Bernstein polynomial B according to Eq. 6. N represents the DoF of the polynomial, r the relative radius position and i the polynomial index. With the parameterisation a modification is defined according to Eq. 6 and the process of adjustments is simplified.

$$(6) \quad B_i^N(r) = \frac{N!}{i!(N-i)!} \cdot r^i \cdot (1-r)^{N-i}$$

The s-shape propeller geometry is parameterised with the factors $A = [0, 0.40, -0.5, 2.1, 0.8, -1.0]$. The specific offset coordinate in y-direction is defined by summing up the the shape functions at each section.

$$(7) \quad \Delta y_{s-sweep}(r) = \sum_{i=0}^{N=5} A_i \cdot B_i(r)$$

Since the shape function defines the maximum deflection at the blade tip to be $\Delta y(r=R) = 1$, the sweep magnitude can be set by adding a sweep magnitude factor $A_{S-shape}$ according to the relative blade radius. For example a sweep magnitude of 10% and a diameter of $D = 2m$ equals a maximum blade tip deflection of $0.1 \cdot 1m = 0.1m$.

The cosinus sweep function is defined as a $1/4$ wave length of the cosinus function and is scaled according to Eq. 8.

$$(8) \quad \Delta y_{cos,sweep,i} = A_{cos,sweep} \cdot \left(1 - \cos\left(r_i \cdot \frac{\pi}{2}\right)\right)$$

The same is valid for the tip modification form with the sweep start position is at $r = 70\%$ according to Eq. 8.

Fig. 5 shows the results of a previous sweep study [30]. The root bending moment is analysed which results from the aerodynamic and structural forces. The x-axis shows the different sweep magnitude relative to the radius. The y-axis shows the relative changes of the maximum root bending moment compared to the reference case. The analysis is performed at a specific operational point which is: $1600RPM$ at $26m^{-s}$ and 20 inflow angle. Fig. 5 shows that the forward swept s-shape form reduces the root bending moment with the highest impact. Since the analysis shown in Fig. 5 is carried out at a specific operational point a case study is necessary to evaluate the effect on a specific use case shown in Chapter 5. Therefore a detailed analysis is performed with a geometric modified propeller with 7.5% forward sweep; compare Chapter 4.

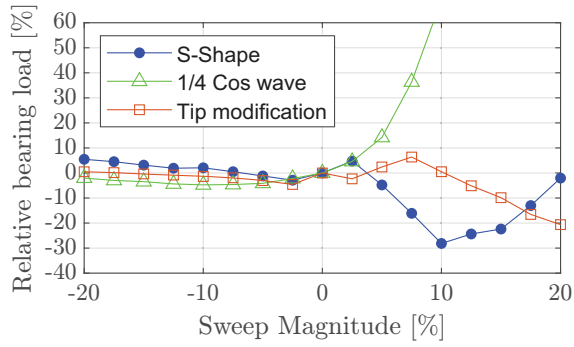


FIG 5. Relative bearing loads of various swept propeller geometries compared to reference [30]

3.2. Precone Angle Modification

A rotating system is affected by longitudinal or centrifugal inertia forces, which can be used to counteract the aerodynamic forces of a propeller blade. A pre-cone angle is geometric modification of a propeller. The blade is leaned out of the rotational plane, with a linear increasing magnitude towards the tip. An out of plane offset is created. The centrifugal forces are approximately constant, however the lever arm which is responsible for the root bending moment increases with the lean magnitude. Hence, a deflected point on the structure out of the rotational axes causes a moment, leading to a restoring moment [31]. The out of plane deflections result either from aerodynamic forces or can be obtained by adding a pre-deflection in form of a pre-cone angle. Thus, the out of plane offset results in a reduction of the mean value of the root bending moment caused by the centrifugal stiffening effect. PropCODE takes the stress stiffening effects into account by adding the geometric stiffness matrix $K^G(F)$ to the equation of motion to be solved at each time step.

3.3. Optimised Propeller Geometry

Fig. 6 shows the unswept reference propeller compared to the s-shaped propeller with 7.5% sweep magnitude. According to the radius the tip of the swept form has an offset in y-direction of 84mm. The optimised propeller form has a pre-cone angle of 1°.

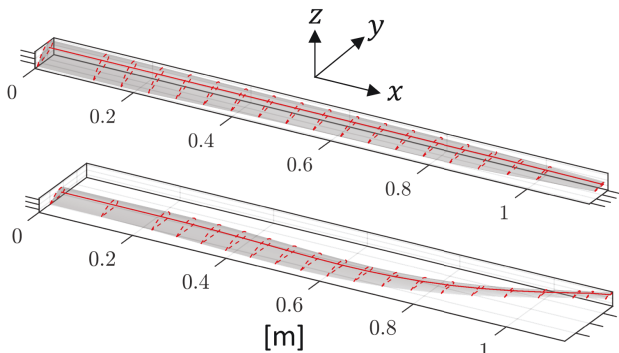


FIG 6. Swept propeller form compared to unswept reference propeller

4. RESULTS

The following Chapter shows the results from the detailed analysis of the s-shape propeller under the influence of oblique inflow conditions. The effect of the dynamic load reduction is shown with details from the aerodynamic and structural simulation process. In order to reduce dynamic loads, analysis is performed on the S-shaped sweep form presented in Fig. 6.

Fig. 7 shows the thrust curves for the reference and the swept propeller with increasing rotational speed on the x-axis. The steady thrust data are computed by taking the elastic deformations derived by the structural module into account. The inflow condition for the hover case is defined with an axial inflow velocity of $v_{hover} = 0.1ms^{-1}$ compared to $v_{hover} = 0ms^{-1}$ for convergence reasons. The design of the swept propeller blade included a trim process to match the design thrust at the design RPM at $1800min^{-1}$. In case of the s-shape propeller, the increasing load results in larger torsional deformations due to torsion-bending coupling. Therefore, the s-shape propeller thrust increases more pronounced than in the case of the unswept propeller. Both propellers are trimmed to match the design thrust at $1800RPM$. This trimmed condition and the steeper thrust slope of the swept propellers results in the s-shaped propeller producing less thrust compared to the unswept propeller for $\Omega < \Omega_{design}$.

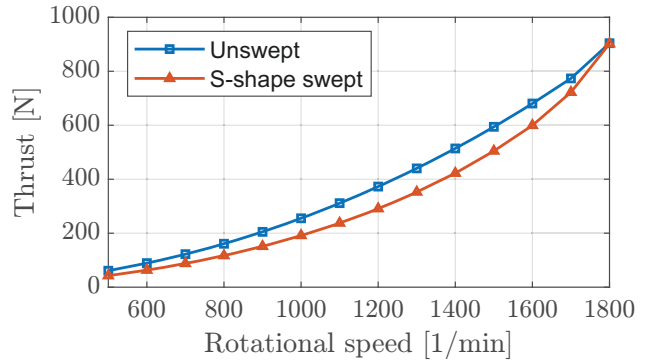


FIG 7. Thrust curve for swept and unswept propeller

After the comparison of the steady aeroelastic performance is completed, the unsteady performance is evaluated. The settings of the aeroelastic unsteady time-marching simulations are listed in Tab. 2. The simulation duration is selected independently, since the convergence depends on the loading condition. After convergence is reached another rotation is performed, which is extracted for postprocessing of the dynamic loads. The structural damping ratio of 1% results from a average value for composite materials [32]. As reference flight state a rotational speed at the design point is chosen. The flight velocity refers to the case study in Chapter 5 where $22ms^{-1}$ is the end of the flight velocity range for the transition from hover to cruise flight.

Parameter	Value
Duration	0.2s
Time step	1ms
Structural damping	0.01
Rotational speed	1800min ⁻¹
Flight velocity	22ms ⁻¹
Inclination angle	20°

TAB 2. Transient solver settings

Unswep propeller results:

The first step of the analysis is the evaluation of the elastic behaviour of the reference propeller compared to the rigid case. By increasing the simulations complexity step wise the accuracy and plausibility of the model can be evaluated since the aerodynamic model itself is validated as well as the structural model. The final validation with experiments of the coupled simulations is outstanding at the moment of the current project NERO and in part presented by Bergmann [9].

Fig. 8 shows the rigid (a) and elastic (b) thrust distribution of the unswept reference propeller shown in Fig. 6. With the incoming air from 180° the top view of the propeller plane is shown with rotational direction being counterclockwise. With the forward flight motion and the oblique inflow an additional velocity component results for the advancing site for $0^\circ \leq \Psi \leq 180^\circ$ of the azimuth position. For the rigid blade (a) the increased velocity component leads to an exponential increase in the lifting force component of the section according to Eq. 9.

$$(9) \quad L_i(r) = \frac{\rho}{2} \cdot v_\infty^2 \cdot c_L \cdot c.$$

By taking the structural behaviour into account the maximum thrust distribution for a revolution shifts by approximately 90° as shown in Fig. 8(b). In helicopter theory this effect is known as phase lag [33] which is valid for a rotor mounted with a flapping hinge. The control inputs are therefore mechanically shifted by -90° to take the phase lag into account and avoid additional pilot workload. In case of the analysed propeller the root is modelled as fixed support. According to van der Wall [34] the eigenfrequency of a hinged rotor is a factor between 1.03 and 1.05 of it's revolution speed. For a hingeless rotor this value increases to range between 1.08 and 1.15. An increased value leads to increased root bending loads and vibrations. In case of the fixed propeller with stiff connection to the root the general phase lag is unknown. For this case the phase lag results from the coupled aeroelastic simulations.

With the inflow velocity with a maximum at $\Psi = 90^\circ$, the quadratic influence on the resulting lift is expressed in Eq. 9. The influence on the resulting force fluctuations along a revolution depends on the velocity difference of the advancing and the retreating side. For the given reference case the ratio between the inflow velocity magnitude and the propeller tip velocity is calculated to:

$$(10) \quad \frac{v_{tip}}{v_\infty} = \frac{\frac{1800}{60} \frac{1}{s} \cdot 2\pi \cdot 1.125m}{22 \frac{m}{s}} = 8.57$$

With lower ratios $\frac{v_{tip}}{v_\infty}$ the resulting loads under oblique inflow conditions at the blade root increase since the relative velocity differences are increased. Hence, reducing the rotational speed will increase the structural dynamic loading for a constant thrust value. According to Möhren [11] an

increase in diameter reduces the dynamic amplitude due to the increasing stress stiffening effect for a constant disk loading. However, an increased diameter results in an decreased rotational speed limit due to the tip speed limitation. Thus, parameters that are responsible for the dynamic loads are coupled to each other.

The increased velocity component on the advancing side increases the absolute aerodynamic moment around the longitudinal axis leading to a reduced AoA. The thrust coefficient c_M is negative with $-0.14 \leq c_M \leq -0.17$ depending on the radial position with the selected airfoil. Consequently, the value reducing the torsional deformation θ and thus the AoA by -1.7° . The resulting lift component is reduced. Regarding the converged quasi-steady simulation between $\Psi = 0^\circ$ and $\Psi = 180^\circ$, the blade is in an upward plunge motion. The upward motion results in an axial velocity component that influences the total inflow direction and thus reduces the effective AoA by -1.3° . The resulting lift component is reduced.

By reaching the retreating side beginning at $\Psi = 180^\circ$ the maximum thrust is reached (Fig. 8b). At this position the negative torsional deformation θ decreases with lower total inflow velocity w . Simultaneously the plunge motion changes it's direction into a downwards motion. The downwards motion results in an upcoming velocity component, which influences the angle of the incoming air. The effective angle of attack (eAoA) takes the changing inflow angle into account. Hence, the downwards motion leads to an increased eAoA. The maximum eAoA is reached at an azimuth position of $\Psi = 250^\circ$ but the reverse flow component reduces the produced lift according to Eq. 9 with an exponential effect.

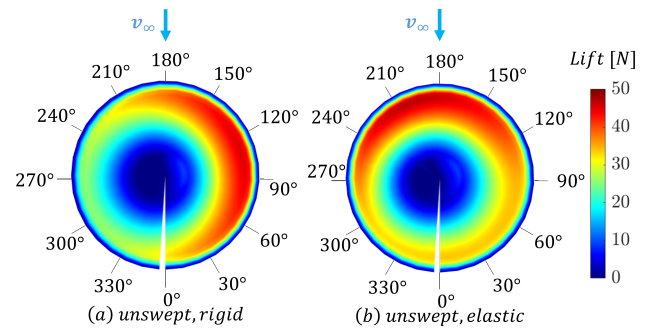


FIG 8. Thrust distribution of (a) rigid vs. (b) elastic propeller at 1800RPM, 22ms⁻¹ and 20° oblique inflow condition

Fig. 9 shows the deformation distribution over a full revolution of the unswept reference propeller. According to the thrust distribution in Fig. 8b the maximum deformation occurs at an azimuth position of $\Psi = 180^\circ$. Compared to the rigid case, the maximum thrust of the elastic blade has a phase lag of 110°. The maximum bending deformation lags by 90° compared to the point of the highest inflow component.

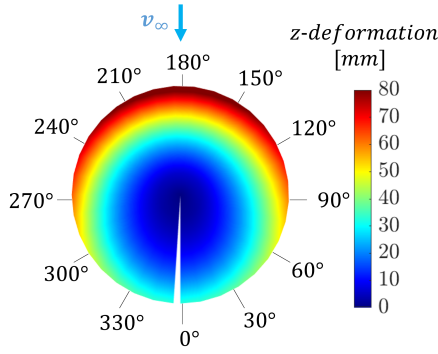


FIG 9. Bending deformation in z-direction for the unswept propeller due to phase lag

For the evaluation of a propeller under oblique inflow conditions the calculation of a single blade as shown up to this point shall be extended to a two bladed propeller system. The bearing loads are calculated by summing up the forces of the single blades. E.g. the lift force of a single blade leads to a stress state at the root, the overall acting moment at the bearing is cancelled out if both blades experience the same forces and moments.

Fig. 10 shows the process of transforming the single blade results into a two bladed propeller with the corresponding hub loading. The x-axis shows the azimuth angle for a single revolution of the propeller blade. The y-axis represents the root bending moment. The single blade (blue) over a full rotation needs to be phase shifted by π to evaluate the opposite second blade (dotted orange). The acting root moments of both blades are then summed up to the '2-Blade local COS' graph (green). Evaluating a two-bladed propeller using the superposition method does not consider the effects of blade interactions or vortex influences. The maximum bearing load is reached at $\Psi = 150^\circ$ or $\Psi = 0.83\pi$ with a value of $120.5 Nm$. In a last step the local bearing loads are transferred from the blade fixed coordinate system to the global coordinate system by the transformation matrices with the corresponding azimuth positions. Per definition of the transformation the global bending moment with respect to the y-axis equals zero at an azimuth position of $\Psi = \pi$. The bending moment around the x-axis is zero at $\Psi = \frac{\pi}{2}$. However, Fig. 10 shows nonzero values. The differences at the sample points result from the aerodynamic and inertial torsional loads of the two propeller blades.

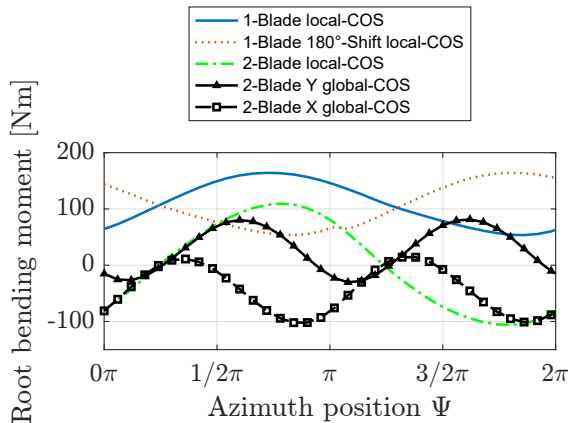


FIG 10. Evaluating 2-bladed propeller from 1-blade simulation run for unswept propeller

Forward s-shape propeller results:

After comparing the unsteady results of the unswept blade, the results of the swept blade are presented. Fig. 11 shows the lift distribution (a) and the deformations (b) of a full revolution of the swept propeller. Compared to the reference case the lift distribution of the swept propeller shows a smoothed distribution leading to a decreased force amplitude and consequently a decreased bearing moment amplitude. Further, the maximum bending deflection position is shifted from $\Psi = 180^\circ$ to $\Psi = 240^\circ$. The phase shift results from the torsional bending coupling of the forward s-shaped swept where higher lift forces result in a positive torsional deformation θ and increase the coupling effect between structural deformations and aerodynamic answers. With the phase shift of the deformations the maximum value of the eAoA is shifted from $\Psi = 230^\circ$ to $\Psi = 310^\circ$, as shown in the appendix Fig. 18.

Two aspects result in the smoothing effect on the lift distribution and consequently the reduction of the local root moments. First, the plunge motion results in an inflow component that affects the eAoA. Second, the torsion-bending coupling causes structural deformations which also affect the eAoA within a blade revolution.

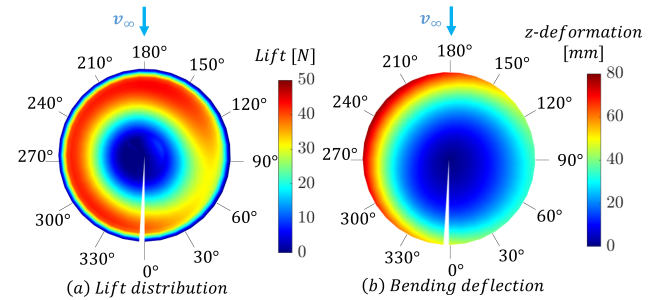


FIG 11. S-shape forward swept propeller transient results (a) thrust and (b) bending deformation

The process of evaluating the two bladed propeller from the single blade analysis is performed according to the unswept propeller. Fig. 12 shows the resulting root bending moments with respect to the local and global coordinate system of the swept propeller. The maximum bearing moment from the single blade is reduced by 48.7%. This reduction is also a consequence of the lean angle of the swept propeller, where the pre-deflection leads to centrifugal forces that counteract the aerodynamic lift.

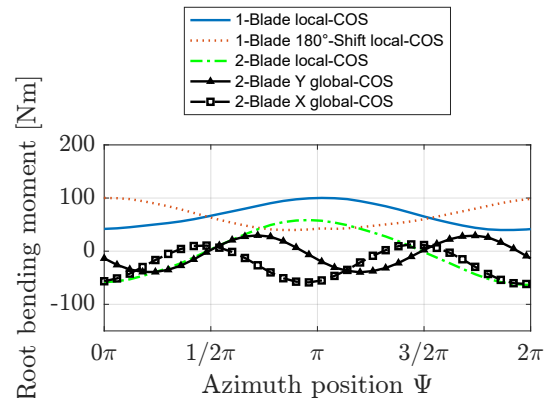


FIG 12. Evaluating 2-bladed propeller from 1-blade simulation run for s-shape swept propeller

Fig. 13 compares the lift distribution of the unswept with the swept propeller geometry. The detailed analyses is pre-

viously shown. In Fig. 13b) the swept propeller shows a smoothed lift distribution compared to the unswept propeller. The peak value within a revolution is reduced by 8.3%. The forces and vibrations that act onto the shaft result from the overlapping loads of both blades of the propeller. If the lift distribution at a specific azimuth position Ψ_0 and the opposite lift distribution $\Psi_1 = \Psi_0 + \pi$ are almost the same, they cancel each other out. Therefore, the dynamic hub loads are reduced.

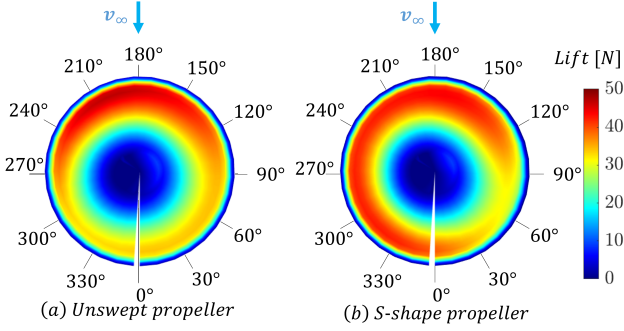


FIG 13. Lift distribution for the (a) unswept and (b) swept propeller

The comparison between Fig. 10 and Fig. 12 results in the data presented in Tab. 3. Tab. 3 shows the amplitude reduction of the global bearing moments M_x and M_y with z being the rotational axis. It must be noted that the given relative values are only valid for the specific comparison on this blade and can differ for other blade geometries and operation points due to the complex behaviour of coupled aeroelastic simulations in the time domain.

Bearing load	Relative amplitude change
$M_{ampl,x,2-blade}$	-38.5%
$M_{ampl,y,2-blade}$	-42.5%
$M_{local,1-blade}$	-48.7%

TAB 3. Bearing load amplitude reduction for design case conditions

5. CASE STUDY

The presented sweep form and possible reduction of dynamic loads shall be demonstrated and further analysed within a case study of a recent eVTOL concept. The eMagic One by MK Technology [35] shown in Fig. 1 uses eight lifting 2-blade propellers of type H26F by Helix Carbon GmbH [29] and a single 3-blade propeller for forward thrust. According to reference [35] the maximum take-off weight is 420kg. With an empty weight of $OEW = 255kg$ and assuming $m_{pilot} = 78kg$ the take of weight is $MTO = 333kg$. Hence, the total lift requirement is 3267N or 408N per propeller. Compared to the design thrust of 905N a safety factor of 2.2 results. Additional safety is given in case of one or multiple engine failures or to be used for extra lift requirement during climb. Tab. 4 shows the technical data given by the manufacturer.

Parameter	Value
Propeller Number	8 + 1
MTOW	420kg
Empty weight	255kg
Wingspan	7.68m
Stall speed	74kmh ⁻¹
Cruise speed	144kmh ⁻¹
Max speed	200kmh ⁻¹
Max cruise duration	60min
Max hover duration	4min

TAB 4. Technical data eMagic One [35]

For the presented case study, several assumptions have been made. The use case of the eMagic One focuses on dynamic loads. Aspects such as flight dynamics and other structural or aerodynamic effects occurring during transition flight are not considered since no model for flight mechanics is implemented. The following assumptions are made for the analysis:

- Lift produced by the wings is not considered for the overall lift requirement during the transition flight which is the scope of this analysis.
- The transition flight is defined between $v_{\infty,0} = 1ms^{-1}$ and $v_{\infty,1} = 22ms^{-1}$. The lifting propellers are then switched off, allowing the wings to produce the necessary lift since the stall speed has been exceeded.
- No acceleration and flight dynamic effects are considered. The sample points of the mission profile have non-accelerated flight speed. Which are: [1, 5, 10, 15, 22]ms⁻¹
- The flight inclination angle is constant at 2°.

Fig. 14 shows the thrust curves for the unswept and swept propeller with the flight speed sampling points. Further, Fig. 14 shows the intersection between the thrust curves with the thrust requirement $T_{requ} = 408N$. The individual rotational speed for the flight speed sampling points are listed in Tab. 5 in the appendix.

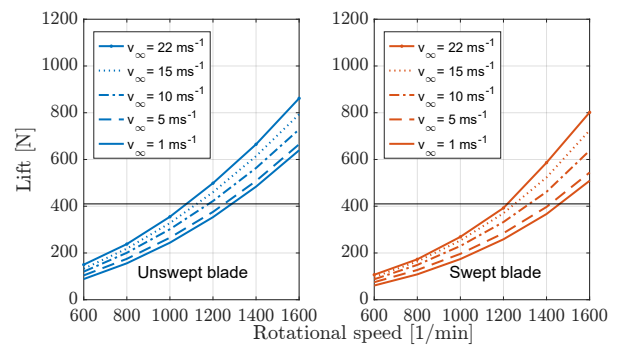


FIG 14. Thrust curves for different flight velocities for the unswept (left) and swept propeller geometry (right)

With the defined matching rotational speeds the occurring dynamic loads are analysed with the methodology shown in Chapter 2. Fig. 15 shows the increasing flight velocity on the x-axis. The y-axis of the upper part represents the total bearing loads of a single blade. The upper part of Fig. 15 further shows the dynamic amplitude for the reference and the swept propeller blade. The lower part of Fig. 15 shows the corresponding relative changes to the reference in percentage on the y-axis. The total root bending load is

reduced between 20.8% and 24.7% depending on the flight velocity. The dynamic amplitude is reduced between 32.2% and 44%.

Two main effects are responsible for the differences:

- *First*, the smoothing of the lift distribution due to the modified torsion-bending coupling due to sweep as shown in Chapter 4.
- *Second*, since the propeller is not operated at its design point, different rotational speeds are necessary for matching the thrust requirement at each flight speed. The rotational speed of the swept propeller is increased. Thus the

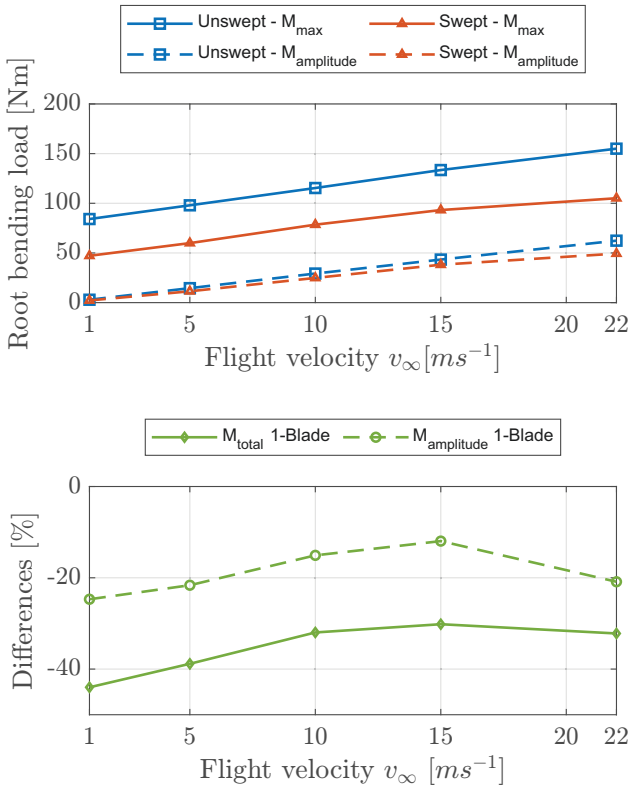


FIG 15. Effect of dynamic load reduction for the specific case study with absolute and relative changes of the root bearing amplitude in the local coordinate system for one blade

Fig. 16 shows the root bending amplitude of the 2-blade propeller. The results for the single blade are transferred into the 2-bladed propeller with the method presented in Chapter 4. The differences are stated for the comparison between the unswept reference propeller and the s-shape swept propeller for the operating points with increasing flight velocity. The strongest relative reduction is -27.0% around the x-axis at a flight velocity of $v_{\infty} = 1 \text{ ms}^{-1}$. The relative change value is between -11.2% and -8.9% within the range of $v_{\infty} = 10 \text{ ms}^{-1}$ and 22 ms^{-1} .

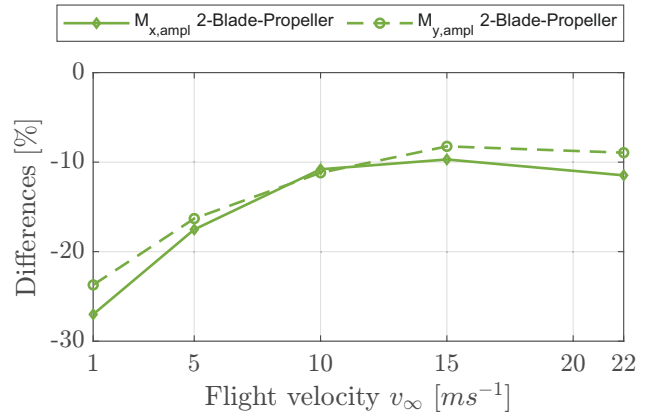


FIG 16. Effect of dynamic load reduction for the specific case study with relative changes of the root bearing amplitude in the global coordinate system for the 2-blade propeller

Conclusively, the effect of reducing the total load and the dynamic amplitude depends on the specific operation condition. Further, a nonlinear behaviour of dynamics loads over increasing flight velocity is observed. The structural behaviour regarding bending deformation primarily depends on the centrifugal stiffening. The influence of the centrifugal stiffening depends on the rotational speed. As aerodynamic forces and moments depend on structural deformation, a coupled analysis is necessary to properly account for torsion-bending coupling. Consequently, the thrust matching rotational speed is determined and the structural loading evaluated.

6. CONCLUSION

The development of modern eVTOL designs that are used for both, hover and cruise flight are affected by dynamic loads under oblique inflow conditions. Lifting propellers used for forward flight in cruise or transition are dynamically excited by the varying inflow velocity component. The resulting forces increase the structural loading in form of vibrations. The research project NERO aims to improve the overall performance and aeroelastic of lifting propellers. The resulting propeller of an optimisation regarding efficiency and reduced noise emissions is used as reference propeller in this paper. The present paper analyses the forward s-shaped propeller regarding the aeroelastic behaviour under oblique inflow conditions.

An analysis performed with PropCODE with the time-marching implicit solver couples the BET for the aerodynamic analysis with the 1-DoF beam theory for the structural analysis. For the case of a rotational speed of 1800RPM, a flight velocity of 22 ms^{-1} and an inclination angle of 20° the occurring root bending moments are evaluated. The results show a relative change of -48.7% compared to the unswept reference propeller. Two aspects are pointed out:

- *First*, the sweep form increases the torsion-bending coupling effecting the AoA over a revolution. Further, the position of maximum deformation regarding twist is delayed. Consequently the swept propeller blade leads to a smoothed lift distribution and thus reducing bending moments for the 2-bladed propeller.
- *Second*, the sweep form increases the torsion-bending coupling effecting the plunge motion over a revolution. It has been demonstrated that by delaying the maximum bending deflection, the axial velocity component resulting

from the plunge motion is overlapping in a different manner with the inflow component from forward flight. Consequently the swept propeller blade leads to a smoothed lift distribution and thus reducing bending moments for the 2-bladed propeller.

A case study demonstrates different flight states of the modern eVTOL eMagic One by MK Technology. The application of a forward s-shaped propeller bladed is evaluated. Assumptions are made to simplify the flight mechanics of the transition flight. Depending on the forward flight velocity, the swept propeller reduces the local root bending moment between 20.8% and 24.7% over all operating points.

The forward s-shaped propeller increases the coupling between aerodynamic forces and moments and the structural response. Occurring effects regarding stability and strength limitations need to be considered within a design process. Further analysis is necessary to evaluate the possible lifespan extension limited by fatigue with the shown reduction in the dynamic amplitude and maximum overall root bending loads limited by material strength. A detailed analysis is requested in order to determine the optimal application for an use case of the forward s-shape propeller due to the complex aeroelastic behaviour.

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7. APPENDIX

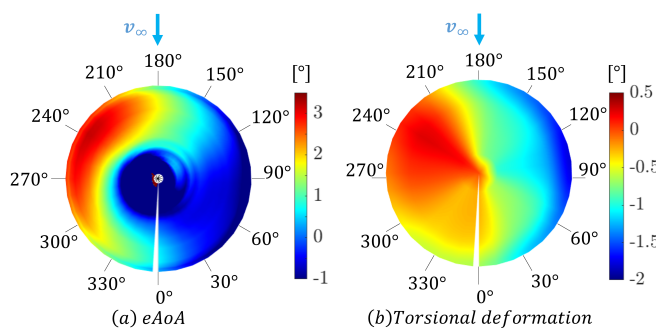


FIG 17. Unswept propeller: torsional deformation and effective angle of attack distribution

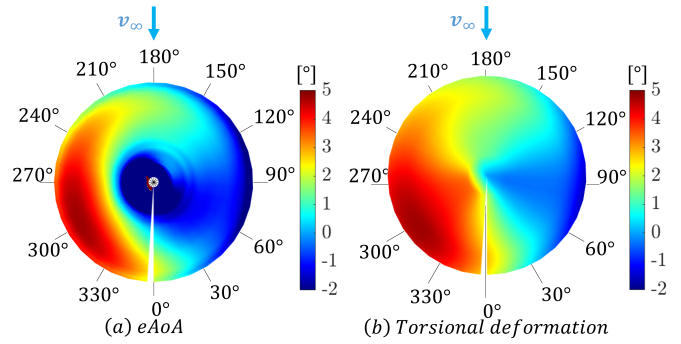


FIG 18. Swept propeller: torsional deformation and effective angle of attack distribution

$v_\infty [\frac{m}{s}]$	Unswept RPM $[\frac{1}{min}]$	Swept RPM $[\frac{1}{min}]$
1	1280	1465
5	1255	1420
10	1180	1327
15	1130	1255
22	1077	1220

TAB 5. Rotational velocities for matching thrust for case study conditions and analysis

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