Sensitivity of Propeller Whirl Flutter With Respect to Blade Parameters

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New methods for propeller whirl flutter prediction emerge, enabling aeroelastic engineers to include more modeling parameters and more sophisticated methods into their analysis. However, the sensitivity of propeller whirl flutter with respect to modeling parameters like airfoil characteristics, blade sweep and stiffness is not clear. This makes it hard to decide, on which blade parameters to focus when choosing a modeling tool or a validation procedure. This paper aims to provide a comprehensive overview of the sensitivity of whirl flutter with respect to the above-mentioned blade parameters, identifying those with the highest impact on stability. For this purpose, the Transfer-Matrix method is used to assess the whirl flutter stability of the simplified pylon model and a generic turboprop aircraft, using a rigid and a flexible set of parametric propeller blades. The results show that blade sweep and an increase in stiffness are strongly destabilizing for whirl flutter. Regarding the blade aerodynamics, the lift characteristics (steady lift offset and lift curve slope) and their radial distribution are the most important aerodynamic parameters, followed by drag and last the airfoil moment characteristics.

Nomenclature

C_{D0}	=	Linear airfoil polar coefficient for the constant, nondimensional drag
C_{L0}	=	Linear airfoil polar coefficient for the constant, nondimensional lift at zero angle of attack
$C_{L\alpha}$	=	Linear airfoil polar coefficient for the nondimensional lift variation with angle of attack
$C_{M\alpha}$	=	Linear airfoil polar coefficient for the nondimensional moment variation with angle of attack
$\frac{dC_{XX}}{dR}$	=	Linear radial variation of the linear airfoil polar coefficient C_{XX}
EI_{ip}	=	Bending stiffness in in-plane direction
EI_{oop}	=	Bending stiffness in out-of-plane direction
GT_T	=	Torsional stiffness
r	=	Radial coordinate
R	=	Propeller radius
V_F	=	Flutter speed
ω_{stab}	=	extension of the whirl flutter region in the stability map

I. Introduction

Whirl flutter is an aeroelastic instability which is important to consider during the design and certification of any propeller-driven aircraft [1, 2]. It presents itself as an instability of the whirl modes emerging from the gyroscopic coupling between the pitch and yaw modes of the engine in its elastic support. Aircraft designers have to consider the aeroelastic stability of these modes alongside load bearing and vibration isolation characteristics when designing, e.g., the engine support system [3]. This requires an accurate flutter prediction to prevent excessive stiffening of the support for extra conservatism. Current trends towards more flexible, high aspect ratio wings in conjunction with high-speed propeller designs further intensify the need for an accurate whirl flutter prediction.

To meet this rising need, new methods are being developed to capture more modeling features during whirl flutter assessment, either in the time domain [4–6] or in the frequency domain [7]. These new methods allow the user to include more parameters into their analysis, such as blade elasticity [6, 8] or more sophisticated propeller aerodynamics [5, 9] with the potential to include full airfoil polars, advanced (swept) blade shapes and transsonic aerodynamics. E.g.,

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they enable the use of 3D potential aerodynamics instead of classical strip-theory based approaches[9] or the inclusion of thrust effects [9, 10]. These new modeling degrees of freedom bring new choices for the user: Some methods, for example, are better in capturing 3D-effects such as tip loss (e.g., 3D potential theory), other better capture the drag and airfoil moment at each section (e.g., via full nonlinear airfoil polars). Naturally, these new analysis capabilities and the required choice of modeling lead to differences in the stability predictions being observed.

Regarding aerodynamic modeling, Gali et al. [5] compared whirl flutter stability results of the simplified pylon system computed via an uniform inflow model with those computed with the viscous vortex particle method (VVPM). They found differences up to 39% in the flutter speed, depending on the advance ratio, blade number and blade chord, using their bifurcation forecasting method. Before, Gennaretti and Greco [11] also compared strip theory approaches with 3D potential theory and found significant differences, in this case for the required suspension stiffness. Koch, Böhnisch et al. [9] conducted a similar study, but also looked into the driving mechanisms behind the differences. The study identifies the unsteady blade aerodynamics as well as azimuthally varying induced velocities as the main drivers behind the alteration of the propeller transfer functions and, therefore, aeroelastic stability. The results were extended to a full aircraft model [12] and give much clearer trends regarding aeroelastic stability, as the simplified pylon model purely contains the propeller transfer functions both as dampening and destabilizing factors. A full aeroelastic aircraft model contains (stabilizing) wing aerodynamics as well, reducing the sensitivity with respect to the stabilizing propeller derivatives. Finally, Gaudemaris et al. [13] also study the effect of angle of attack on whirl flutter stability, finding a slightly stabilizing influence at higher angles of attack due to the effect of nonlinear lift slope at higher blade angles of attack.

Regarding blade elasticity, Hoover and Shen [6], demonstrated the stabilizing effect of blade flexibility on whirl flutter stability. Koch and Koert [8] traced down this stabilizing effect to cyclic blade deformations due to the azimuthally varying airload on the blades during propeller disc pitch motion. The effect is driven partially by the ratio between rotational speed and first blade eigenfrequency and partially by the blade stiffness itself. Noël et al. [14] demonstrated that this stabilizing effect can also be observed for full aircraft models and further studied the impact of stiffness scaling.

Although most of these studies look into the differences in propeller whirl flutter stability predictions with different methods and modeling approaches, and also look into some modeling parameters, a common understanding of the sensitivity of stability results with respect to individual model parameters (such as blade lift curve slope, drag and moment coefficients or individual blade stiffnesses) is missing. Using legacy methods, Cecrdle studied the isolated influence of the radial blade lift curve slope distribution [15] and concluded it was a relevant parameter for stability predictions. The aim of this study is to extend these studies to a more comprehensive set of blade modeling parameters using state of the art stability analysis methods. The methodology for this is delineated in section II, including a description of the model used as well as the set of parameters investigated in the sensitivity study. The results including the influence of blade parameters on individual propeller derivatives as well as the aeroelastic stability of the simplified pylon system as well a generic full aircraft model are presented in section III, followed by a conclusion and common discussion. The overall purpose is to shed a light on the relevance of certain modeling parameters for propeller whirl flutter prediction, so that the user can choose methods and validation tools to focus on these sensitive parameters first.

II. Methodology

To conduct the whirl flutter analysis, the Transfer-Matrix (or TM-) method is used in this paper to represent the aeroelastic propeller in a frequency-domain flutter analysis [7, 16]. The first subsection gives a rough outline of the method, for more information the reader is referred to previous publications [7–9, 16]. After describing the TM-method, the parametric propeller blade used in this study is introduced, as well as the aircraft models used for stability analysis.

A. Transfer-Matrix method

The fundamental concept of the Transfer-Matrix method is based on identifying frequency-domain transfer functions from propeller hub displacements to propeller hub loads by perturbing a time-domain simulation model of the isolated propeller with forced motion about its hub [7]. The resulting linear relation connects the six hub motion degrees of freedom (DOF) $\Delta \boldsymbol{x}_{hub}$ with the resulting six load components $\boldsymbol{F}_{prop,hub}$, as shown in Eq. 1. The transfer function $\underline{H}_{prop}$ connecting the two is a complex-valued, frequency-dependent six-by-six transfer matrix. The transfer matrices are furthermore dependent on the propeller operating point, e.g., the airspeed V and the shaft rotational speed Ω.

$$\boldsymbol{F}_{prop,hub} = \underline{H}_{prop}(i\omega, V, \Omega, Ma)\, \Delta \boldsymbol{x}_{hub} \tag{1}$$

Figure 1 [16] summarizes the main steps for the TM-method. During the first step, the transfer matrices are identified using time-simulations for pulse perturbations of the hub motion about a trimmed reference flight condition. The identified scalar transfer functions are assembled to the transfer matrix $\underline{H}_{prop}$ for a set of base frequencies. After some post-processing steps [14], e.g., removing unwanted mass and gyroscopic terms from the transfer matrices, $\underline{H}_{prop}(i\omega)$ can be used in a frequency-domain flutter analysis.

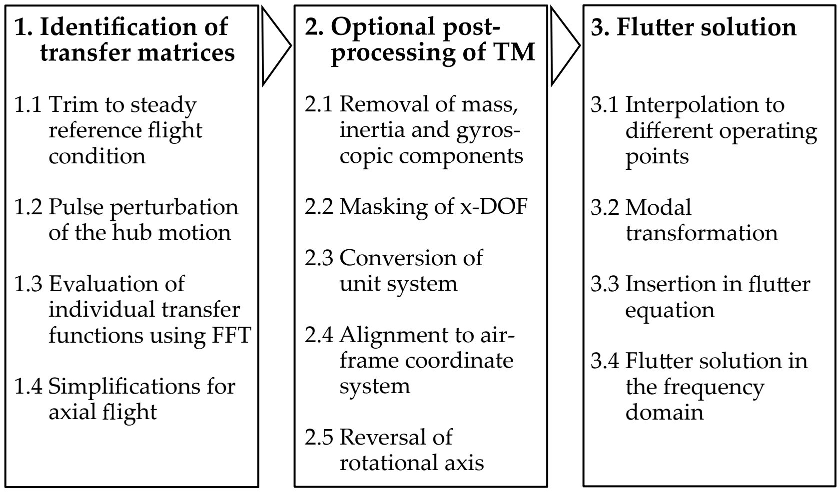

Fig. 1 Workflow for the Transfer-Matrix method, reproduced from [16]

Equation 2 shows the frequency-domain flutter equation for an aeroelastic aircraft, with the structural stiffness, damping and mass terms in generalized coordinates on the left-hand side, unsteady aerodynamics from lifting surfaces on the right side represented as frequency-dependent $\underline{Q}_{gen}(ik, Ma)$, and the generalized transfer matrices $\underline{H}_{gen,prop}$. The latter are obtained from the identified transfer matrices by pre- and post-multiplication of the modal matrix [7].

$$\left[s^2\underline{M}_{gen} + s\underline{D}_{gen} + \underline{K}_{gen}\right]\boldsymbol{q} = \frac{\rho}{2}V^2\underline{Q}_{gen}(ik, Ma)\boldsymbol{q} + \underline{H}_{gen,prop}(i\omega, V, \Omega, Ma)\boldsymbol{q} \tag{2}$$

Solving Eq. 2 for its eigenvalues, e.g. using classical flutter solution techniques [7], gives the frequency and damping of the aeroelastic system eigenmodes and allows a stability assessment.

To assess the impact of parameter changes on the transfer matrices and therefore on stability, it can be useful to linearize the frequency-dependent $\underline{H}_{gen,prop}$ with respect to frequency and obtain stiffness and damping derivatives similar to those used in legacy methods [9]. This approach is used in this paper purely for visualization purposes of the transfer matrices, as using the derivatives also in the flutter analysis does not yield exact results [12].

B. Blade modeling

The propeller model used in this study to identify the transfer matrices was built and used already in previous publications by the author [8]. It is a multi-body simulation (MBS) model for the commercial MBS Simpack [17] and represents a five-bladed, wooden turboprop propeller. The MBS model uses beam elements for the elastic blade model (which can be set to rigid for a rigid-blade analysis) and uses unsteady strip theory without inflow modeling for the aerodynamics [18]. Unsteady strip theory overestimates the unsteady propeller loads compared to more sophisticated models [9], but still retains the main effects and is chosen for the study due to its computational speed and availability in Simpack. The nominal modeling parameters (airfoil polars, stiffness distribution) are taken from Koch and Koert [8] and are listed in Tab. 1. The nominal stiffness values for bending and torsion (last three rows) are multiplied by a factor of four compared to the previous study to obtain an unstable system even with elastic blade formulation. The eigenfrequency of the first non-rotating eigenmode (first out-of-plane (oop) bending) is 62 Hz.

The aerodynamic parameters consist of the classical parameters for a linear airfoil polar. Their radial distribution is varied both constantly and linearly with the radius (compare column two in Tab. 1). Most parameters are varied in both positive and negative direction, although only the positive change is shown in the results later, the negative variation was used for cross-checking purposes only. In addition to the airfoil polar parameters, a simplified model for sweep in

Table 1 Parameters for the sensitivity study.

Parameter	Distribution	Min. value	Nominal	Max. value
$C_{L\alpha}(r)$	$C_{L\alpha} + 2(\frac{r}{R} - 0.5)\frac{dC_{L\alpha}}{dr}$	5.9305	6.5894	7.2483
$C_{L0}(r)$	$C_{L0} + 2(\frac{r}{R} - 0.5)\frac{dC_{L0}}{dr}$	-0.5	0.0	0.5
$C_{M\alpha}(r)$	$C_{M\alpha} + 2(\frac{r}{R} - 0.5)\frac{dC_{M\alpha}}{dr}$	-0.2	0.0	0.2
$C_{D0}(r)$	$C_{D0} + 2(\frac{r}{R} - 0.5)\frac{dC_{D0}}{dr}$	0.0	0.0	0.015
Sweep	Sweep $\cdot \frac{r^2}{R^2}$	0.0	0.0	0.1
$EI_{oop}(r)$	$EI_{oop,ref}(r)\ k_{scale}$	0.9	1.0	1.1
$EI_{ip}(r)$	$EI_{ip,ref}(r)\ k_{scale}$	0.9	1.0	1.1
$GT_T(r)$	$GT_{T,ref}(r)\ k_{scale}$	0.9	1.0	1.1

chord-wise direction is introduced by simply offsetting the airfoil sections in the direction of the chord. No aerodynamic corrections for sweep but a shift in the collocation points for lift and downwash are taken into account. The stiffness distribution is varied in out-of-plane (oop) and in-plane (ip) direction as well as for torsion by applying a constant scaling factor (see Tab. 1). Out-of-plane and in-plane are defined with respect to the twisted, but unpitched propeller blade (twist distribution is given in [8]), not with respect to the local chord. Cross-coupling terms in the stiffness matrix are not scaled.

Each parameter is changed individually in this sensitivity study. For the aerodynamic parameters, the constant and linear variation is also applied separately. Two sets of transfer matrices are obtained, one for a rigid set of blades, varying only the aerodynamic parameters (those above the mid-line in Tab. 1), and one for the elastic reference blades, including all parameters in the study. For each parameter variation, the model is trimmed for a reference operating point (sea-level conditions, 142 m/s airspeed and 1600 rpm shaft speed) to windmilling conditions (zero power/torque) by adjusting the blade pitch setting. Therefore the trim point can be different, especially when considering a lift offset C_{L0} or drag C_{D0}.

C. Stability analysis models

The identified transfer matrices for each parameter variation are used in this paper for the whirl flutter stability assessment of two aeroelastic aircraft models. The first is the simplified pylon model with two DOF widely used in the literature to study basic whirl flutter effects [16]. The second represents a full, free-flying propeller aircraft and also includes unsteady aircraft aerodynamics [14]. The models and the connected analysis details for this study are briefly introduced in the following subsections.

1. Simplified pylon model

The simplified pylon model represents the most basic model to predict whirl flutter and is widely used due to its simplicity. It features a rigid engine model supported by two springs allowing a pitch and yaw motion about a pivot point with distance a behind the propeller plane (compare Fig. 2). The model data used here for the pitch, yaw and polar inertia are given in [16]. The model is assessed for its whirl flutter stability with a fixed operating point and varying pivot stiffness combinations, resulting in a stability map for the engine support stiffness (given in uncoupled frequencies $\omega_{pitch} = \sqrt{K_{pitch}/I_{pitch}}$) as depicted in Fig. 3. The extent of the unstable area under the bell curve on the bottom left is used as a measure for whirl flutter stability. A larger extent, represented by the vertex of the bell-curve on the line of equal pitch and yaw stiffness, means a more unstable aeroelastic system.

$$\Delta\omega_{stab,i} = \frac{\omega_{stab,i} - \omega_{stab,ref}}{\omega_{stab,ref}} \quad (3)$$

$\Delta\omega_{stab}$ as defined in Eq. 3 is used as a non-dimensional measure of the shift of the vertex due to a parameter variation compared to the nominal system. A positive $\Delta\omega_{stab}$ represents a more unstable system.

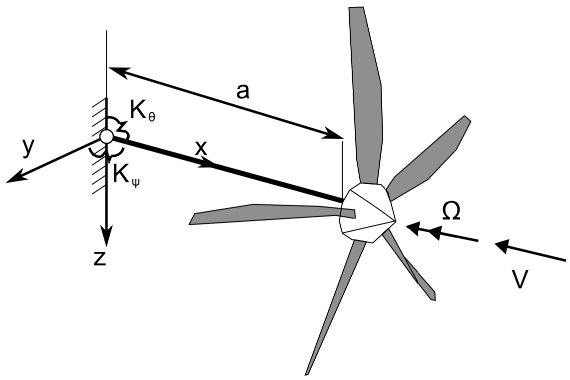

Fig. 2 Simplified pylon system for whirl flutter analysis [16]

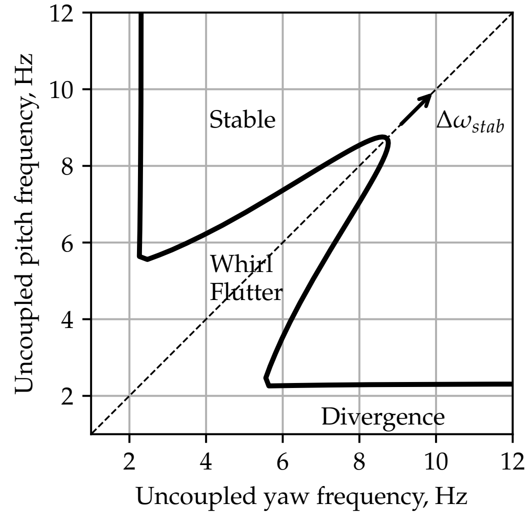

Fig. 3 Example of a whirl flutter stability map.

2. Generic turboprop aircraft model

As a more realistic example, a full, free-flying aircraft model of a generic, twin-engine turboprop aircraft is used [14]. The structural model comprises a full-aircraft finite element model, which is represented by the first 50 eigenmodes, including six rigid-body modes. The unsteady aerodynamics of the lifting surfaces is included into the flutter analysis using $\underline{Q}_{gen}(ik, Ma)$, computed using the doublet-lattice method (DLM) in ZAERO [19]. The ZAERO model is shown in Fig. 4. Infinite-plate splines are used to spline the aerodynamic to the structural model.

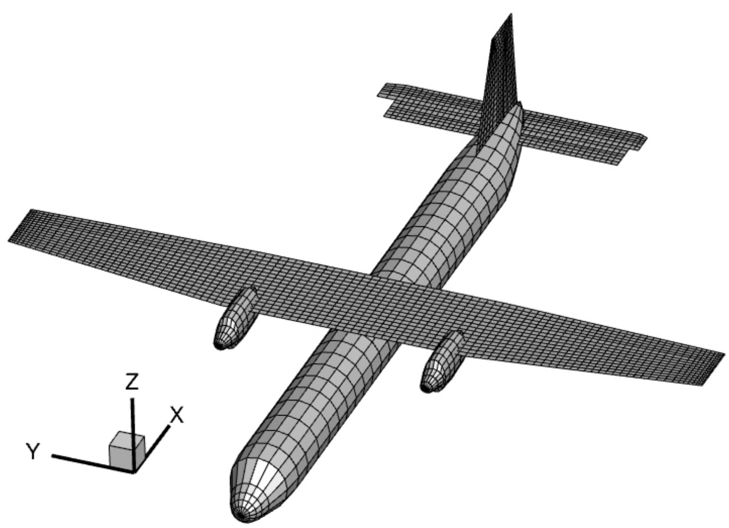

Fig. 4 Aircraft geometry represented by the aerodynamic mesh of the ZAERO model, reproduced from [14].

For each parameter combination, a flutter analysis is conducted between 0 and 170 m/s true airspeed. Therefore, several sets of transfer matrices at different operating points (0.25, 0.5, 0.75, 1.0 and 1.2 times the nominal airspeed) are identified to conduct the flutter analysis for each blade parameter set. From the identified matrices, all intermediate operating points are obtained by cubic interpolation. The flutter speed of the first unstable elastic mode is used as a measure of instability. Its variation ΔV_F with a change in blade parameters represents the sensitivity of the whirl flutter stability with respect to that parameter.

III. Results

This section presents the result of the simulation study conducted to uncover the sensitivities of whirl flutter with respect to blade parameters. First, the sensitivities of the identified transfer functions are presented, together with their nominal values for rigid and elastic blades. The second subsection presents whirl flutter stability results for the simplified pylon system, comparing the change in required suspension stiffness and the influence of parameter variations. The last subsection finally deals with the sensitivity of the whirl flutter speed of the generic turboprop aircraft with respect to the blade parameters.

A. Sensitivity of transfer functions

Before perturbing each individual system to derive the transfer matrices, each propeller model is trimmed to windmilling conditions at zero torque. Due to the absence of drag in the nominal parameter set, strip theory also delivers zero thrust for most of these trim points, only for those with altered drag coefficient a negative thrust coefficient is required to reach windmilling conditions ($C_T = -0.173$ for rigid blades and a constant increase in C_{D0} along the radius). Most trims give an almost identical blade pitch setting of additional 30deg compared to the unpitched blade. Only altering the constant lift offset on the blade has a major impact on the pitch setting (max. +4.35deg deviation for rigid blades and a decrease of C_{L0} to -0.5).

For each individual parameter from Tab. 1 and both for rigid and elastic blades, a set of frequency-dependent transfer matrices is identified. The transfer matrices are linearized with respect to frequency to compare them more easily [9]. Tab. 5 shows the eight unique derivatives with respect to pitch motion (the derivatives for yaw motion derive from symmetry [20]). The second column gives the numerical values for rigid propeller blades, while the third gives the derivatives for flexible blades. When comparing signs of the derivatives, mind the rotational direction of the propeller, which is clock-wise looking from the front. [9, Fig. 2] provides the sensitivity of the simplified pylon system with respect to the individual derivatives, identifying $C_{n\theta}$ (and C_{zq}) as the main destabilizing and $C_{y\theta}$, $C_{z\theta}$ and C_{mq} as the main stabilizing derivatives. As expected, blade flexibility alters all these transfer functions [8]. The influence is stabilizing, as Fig. 6 demonstrates with a comparison of the rigid and flexible stability map for the simplified pylon system. The reason is found especially in a decrease in the destabilizing coupling moment derivative $C_{n\theta}$ as well as an increase in the stabilizing derivatives $C_{y\theta}$ and C_{mq}.

Fig. 5 Propeller derivatives for the nominal blade sets.

Derivative	Rigid	Flex
$C_{y\theta}$	-0.0625	-0.0812
$C_{z\theta}$	-0.3598	-0.3529
$C_{m\theta}$	0.0189	0.0275
$C_{n\theta}$	0.0875	0.0842
C_{yq}	0.2048	0.2403
C_{zq}	-0.0261	-0.0371
C_{mq}	-0.0754	-0.0800
C_{nq}	0.0118	0.0137

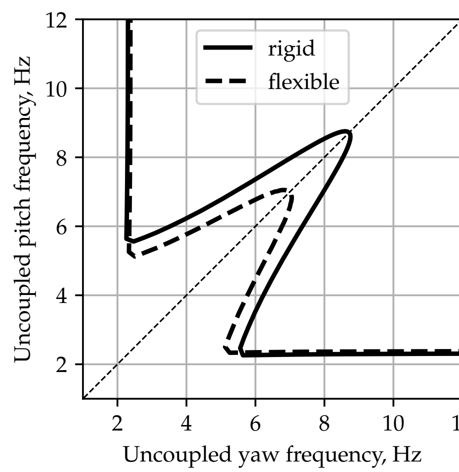

Fig. 6 Nominal whirl flutter stability maps for rigid and elastic blades.

Figure 7 shows the variation of the individual derivatives due to a change in the respective blade parameter in terms of percentage of the nominal value. The amplitude of the change in parameter is given in Tab. 1. Blue bars indicate the variation for rigid blades, orange bars the variation for flexible blades. The top four plots show the stabilizing derivatives, an increase in magnitude increases stability. The bottom two plots list the two destabilizing components, where an increase in magnitude decreases stability. C_{yq} and C_{nq} are omitted due to their negligible influence on whirl flutter. The six plots are sorted according to importance, e.g. C_{mq} is the main stabilizing derivative and $C_{n\theta}$ main destabilizing component. Care must be taken when interpreting changes in individual derivatives, as force and moment derivatives are weighted by the mode shape of the whirl mode (translation vs. rotation of hub node) and stabilizing and destabilizing components can cancel each other (compare [9] for a more in-depth discussion).

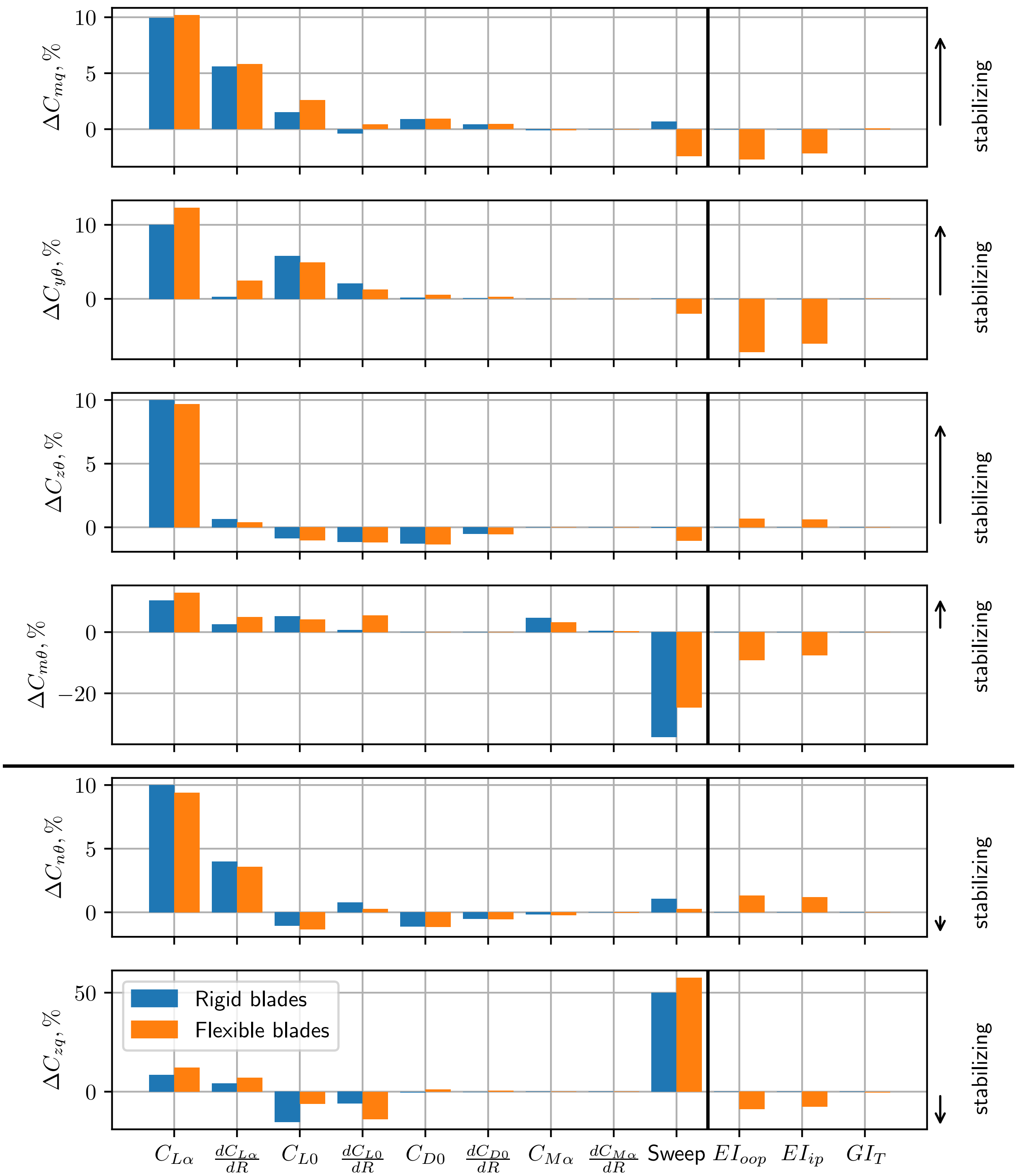

Fig. 7 Sensitivity of the individual propeller derivatives with respect to blade modeling parameters.

The two driving parameters for the derivatives are the lift curve slope $C_{L\alpha}$ and blade sweep. A ten percent increase in $C_{L\alpha}$ increases the rigid blade derivatives equally by ten percent (in their analytical derivation, they linearly depend on $C_{l\alpha}$ [20]). Blade sweep decreases $C_{m\theta}$ and significantly increases the damping force in vertical direction, C_{zq}, by almost fifty percent. The steady lift distribution along the blade, mainly influenced by altering C_{L0} and $\frac{dC_{L0}}{dR}$, also influences almost all derivatives, in general increasing the stabilizing and descreasing the destabilizing ones. Drag decreases $C_{z\theta}$ due to the negative static thrust in this trim point, while it also decreases $C_{n\theta}$ and increases pitch damping C_{mq}. Airfoil moment coefficients only impact the pitch moment due to steady pitch angle $C_{m\theta}$. In general, the linear variation of the airfoil parameters $\frac{dC_{XY}}{dR}$ has a smaller influence on the derivatives and therefore on the transfer matrices than the constant offset.

The sensitivities are very similar when comparing between rigid and elastic blades, although in some cases the magnitude differ more significantly or show opposite trends (e.g., change in C_{mq} due to blade sweep). For the three parameters only covered for elastic blades, an increase in blade bending stiffness clearly decreases the stabilizing derivatives and increases $C_n\theta$, hinting at a destabilizing influence. Torsional stiffness does not impact any derivative significantly.

B. Sensitivity for simplified pylon system

While looking into the transfer matrices and the propeller derivatives gives an insight into the effect of the blade parameters on the unsteady propeller aerodynamics, it can be misleading in terms of effect on the aeroelastic stability [9]. Fig. 8 shows the sensitivity of the whirl flutter stability of the simplified pylon system due to changes in the blade parameters, given in terms of a relative shift of the whirl flutter stability boundary (see Eq. 3 and Fig. 6 for the nominal boundaries). A negative $\Delta\omega_{stab}$ signals a more stable system, a positive value a destabilizing influence of parameter X. For example, an increase of C_{L0} to 0.5 (according to Tab. 1) has a stabilizing influence in the whirl flutter stability of the simplified pylon system by decreasing the extend of the whirl flutter area by about four percent for rigid blades.

The main stabilizing parameters are the steady lift distribution C_{L0} and airfoil drag C_{D0}, both for rigid and elastic blades. Sweep is the main destabilizing parameter for rigid blades, as is an outboard shift in radial lift curve slope $\frac{dC_{L\alpha}}{dR}$. For elastic blades, sweep and an increase in in- and out-of-plane bending stiffness are the driving destabilizing parameters, shifting the flutter point in terms of engine support frequency by almost eight percent for a backward-swept blade. While a constant increase in C_{L0} is strongly stabilizing, an outboard shift in the steady lift $\frac{dC_{L0}}{dR}$ has a small destabilizing influence on the rigid blade analysis, but still stabilizes the flexible blade analysis. This contradicting effect can be explained by the steady blade deformations cause by the radial shift of the lift towards the more flexible propeller blade tip [8]. Most other parameters though show a similar trend between rigid and elastic blades.

An interesting effect can be observed for an increase in $C_{L\alpha}$. Although this heavily affects the propeller derivatives (see Fig. 7), the effect on aeroelastic stability on the simplified pylon system is small. This is due to a cancellation effect. The aeroelastic stability of the simplified pylon system is defined by an equilibrium between stabilizing and destabilizing terms in the equations of motion, which in this case are purely the propeller derivatives due to the lack of structural damping and wing aerodynamics. Scaling both sides of this balance has a canceling effect, so the stability remains almost constant. For C_{L0}, where the magnitude of changes in the derivatives is much smaller compared to $C_{L\alpha}$ (see Fig. 7), but uneven across the derivatives, the resulting effect on stability is much stronger. These cancellation effects are an artifact of the simplified aeroelastic system represented by the 2-DOF pylon system.

C. Sensitivity for generic turboprop aircraft

To overcome these disadvantages, a flutter analysis study is conducted on a more complex aeroelastic system, the generic turboprop aircraft shown in Fig. 4. Before the effect of the parameters on the flutter stability of this configuration is presented, Fig. 9 and Fig. 10 show the nominal flutter results for rigid and elastic blades respectively. More details about the nominal flutter cases can be found in Noël et al. [14]. The critical whirl flutter mode with the lowest flutter speed is marked with solid black line in the respective frequency and damping plots. The flutter points (airspeed at which the damping crosses the axis of zero damping) are at 135 m/s for rigid blades and at 152 m/s for the elastic blade case (remember the stiffness-factor of four compared to the nominal elastic blades in [14]). Both instabilities represent a backward whirl flutter of both engines, with an in-phase whirl-motion counterclockwise looking from the front.

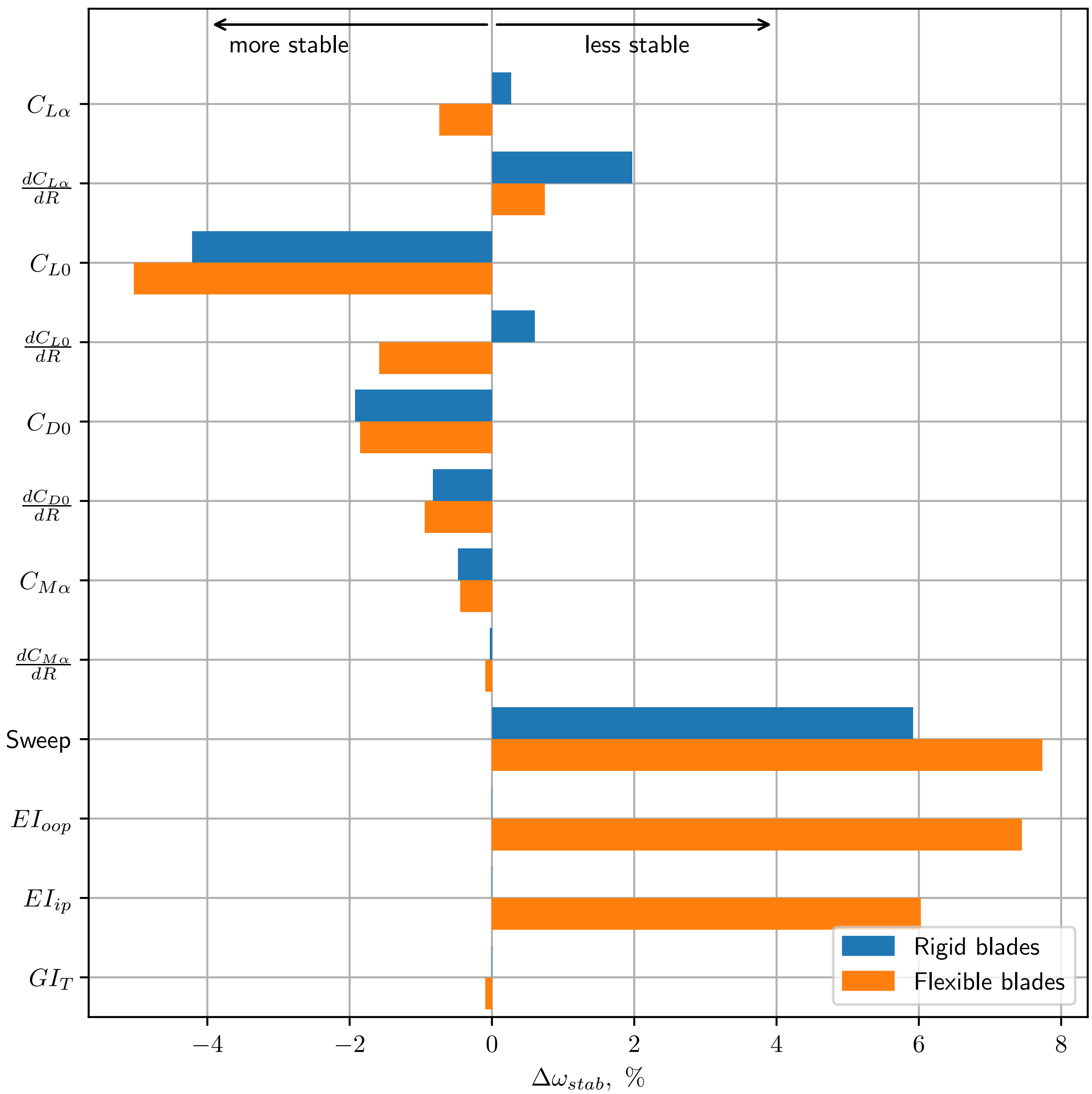

Fig. 8 Sensitivity of the whirl flutters stability of the simplified pylon system, given in terms of a relative shift in the stability map (compare Eq. 3).

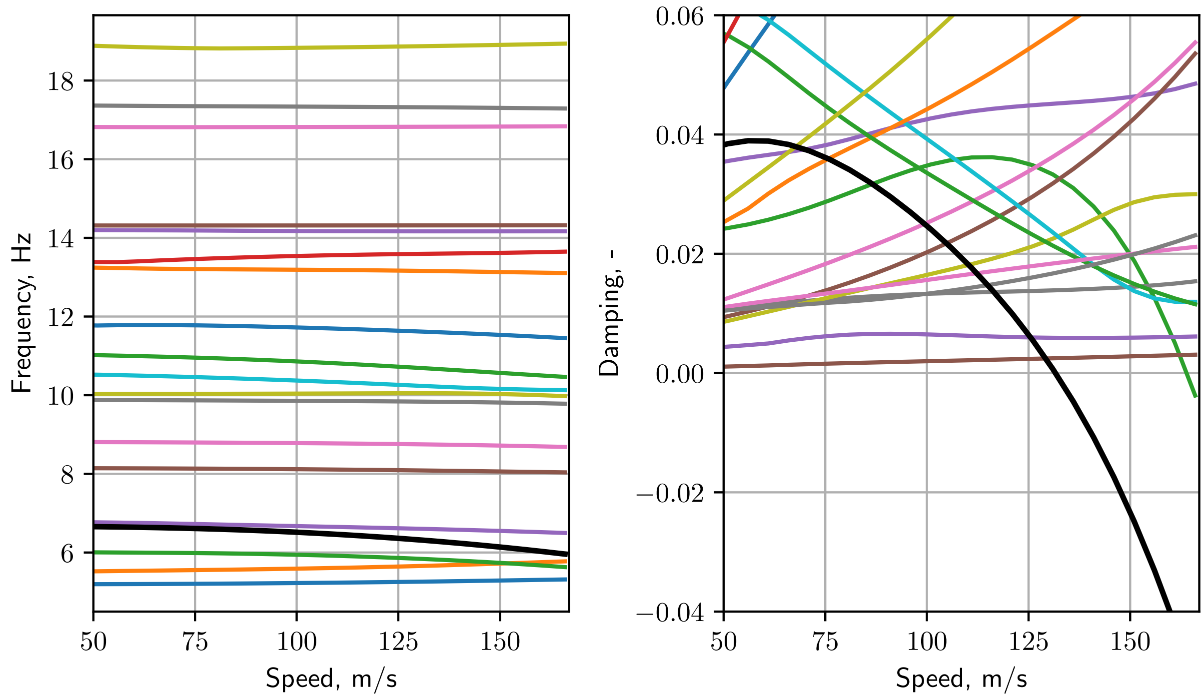

Fig. 9 Frequency and damping trends for the generic turboprop aircraft using the nominal rigid blade set.

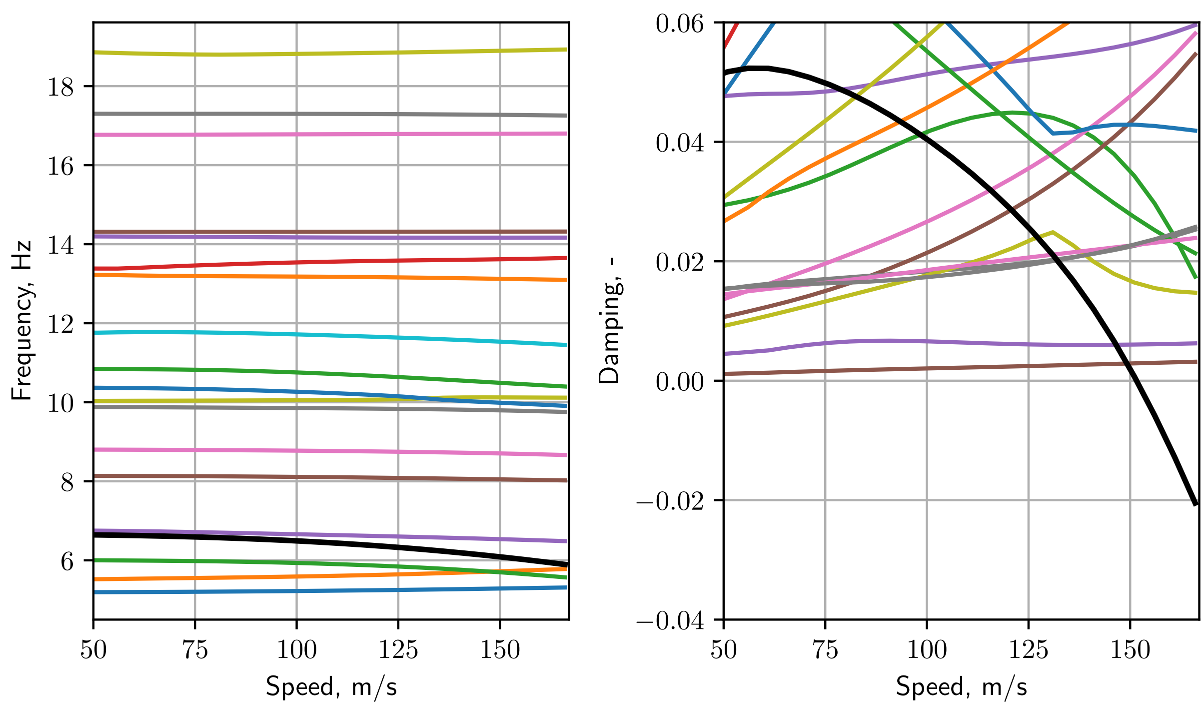

Fig. 10 Frequency and damping trends for the generic turboprop aircraft using the nominal flexible blade set.

Figure 11 finally shows the absolute shift in flutter speed relative to the nominal configuration for a positive change in the parameters defined in Tab. 1. Here, opposed to Fig. 8, a negative value represents a more unstable system, as this indicates a flutter point at a lower airspeed.

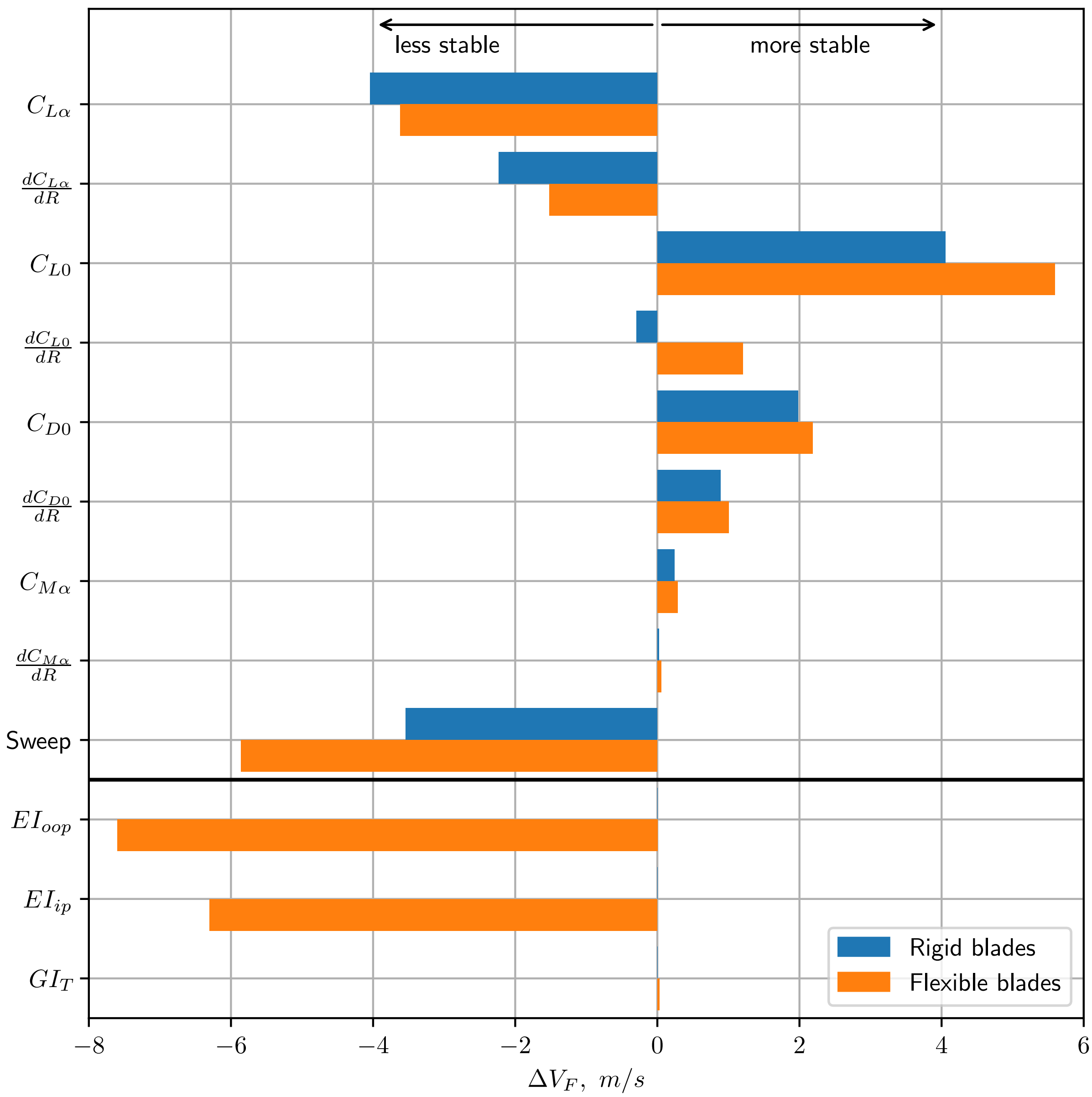

Fig. 11 Sensitivity of the flutter speed of the generic turboprop aircraft with respect to blade parameters.

Comparing the trends between Fig. 11 and Fig. 8, most parameter sensitivities stay similar. A constant airfoil lift offset C_{L0} and airfoil drag C_{D0} are still the main stabilizing parameters, while sweep and blade bending stiffness are still the main destabilizing parameters. Only for the effect of the lift curve slope $C_{L\alpha}$ and its radial distribution, the results for the full aircraft model are very different to those of the simplified pylon system. While for the latter, cancellation effects result in an unclear picture regarding whirl flutter stability, both parameters have a clear destabilizing effect on the generic turboprop model. For this configuration, in the flutter point the destabilizing pitch-yaw coupling moment $C_{n\theta}$ is counterbalanced also by wing aerodynamic damping, reducing the overall sensitivity with respect to the stabilizing propeller derivatives [12]. $C_{n\theta}$ increases in amplitude due to an increase in $C_{L\alpha}$, therefore the system becomes unstable at a lower airspeed. Airfoil moment characteristics as well as torsional stiffness do not show any major impact on flutter stability, both for the simplified pylon system as well as the generic turboprop model. For most parameters, elastic blades increase the sensitivity of the flutter speed with respect to the blade parameters compared to rigid blade. This can especially be observed for C_{L0} and blade sweep.

IV. Conclusion and Discussion

This study uncovered the sensitivity of propeller whirl flutter with respect to blade parameters such as airfoil coefficients, blade sweep and blade stiffness. The Transfer-Matrix method was used to derive frequency-domain transfer functions from a set of parametric, time-domain propeller models in the MBS software Simpack. Starting from a rigid and an elastic nominal blade, one blade parameter at a time was varied and the resulting transfer matrices used to study the whirl flutter stability of the simplified pylon model and a generic turboprop aircraft.

The results showed that for the aerodynamic parameters, the lift characteristics (steady lift C_{L0} as well as lift curve slope $C_{L\alpha}$) and their radial distributions are important parameters for stability. Drag has a stabilizing influence (smaller than that of steady lift) and airfoil moments are almost negligible. Blade backward sweep has a strong destabilizing influence. Sweep was not accounted for in legacy methods but is a very important design characteristic especially for propeller blades designed for high-speed conditions. Elastic blade modeling increases the destabilizing effect of sweep even further. As expected, increasing blade bending stiffness destabilized the backward whirl flutter mode, reducing the overall stabilization of blade flexibility itself. No large difference between the effect of in-plane and out-of-plane bending stiffness was found, which can partly be attributed to the global definition of in- and out-of-plane directions.

From these findings, some conclusions regarding the choice of methods for aeroelastic modeling of propeller can be drawn. As the lift characteristics along the blade are of primary interest, care should be taken to properly include tip-loss and hub effects to achieve a realistic steady and unsteady lift distribution. Due to the stabilizing influence of drag and the small influence of the airfoil moment, these remain of smaller importance. The effect of sweep should be studied more in detail, with aerodynamic methods that capture more relevant effects on the aerodynamics than the simple strip-theory used in this study. Earlier findings on the importance of blade elastic modeling are also confirmed in this study, as blade bending stiffness shows the largest overall sensitivity values with regards to the flutter speed of the generic turboprop aircraft. While this study only analyses linear sensitivity with varying one parameter only, potential cross-sensitivities and the effect of nonlinearities could be addressed using uncertainty quantification methods.

The results of this study should help aeroelastic engineers concerned about propeller whirl flutter stability to choose their modeling tools and methods and set the right focus when beginning to validate their models. Validating the structural model of the blades using structural dynamic testing for stiffness and eigenfrequencies can increase the confidence in the elastic model and reduce sensitivity towards modeling errors there. With regards to aerodynamic data, using mid- or high-fidelity tools to achieve a realistic unsteady blade lift distributions is advisable. Detailed characteristics like drag and airfoil moment, which require expensive computational methods such as unsteady CFD, are of minor relevance.

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