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WHIRL FLUTTER STABILITY ANALYSIS OF PROPELLER AIRCRAFT

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ABSTRACT

Propeller whirl flutter is a type of instability that limits the flight envelope in various aircraft designs such as turboprop, pistonprop, and electric propeller aircraft. To ensure the safety and integrity of the aircraft, whirl instability has to be eliminated from the aeroelastic flight envelope of the aircraft. Within this context, we employ a numerical approach using MSC Nastran to analyze whirl flutter instability for propeller aircraft. The whirl flutter analysis of two sample problems namely, D-1807 propeller and BAH wing/engine configurations were performed to obtain the flutter boundaries. In the course of these analyses, a preprocessor program installed along within MSC NASTRAN was utilized to prepare the propeller aerodynamic matrices.

INTRODUCTION

The concept of propeller whirl flutter was initially discovered and analytically investigated by Taylor and Browne in 1938. In the following decades, two fatal accidents of Lockheed Electra aircraft occurred over the interval of a year. Following these accidents, several wind-tunnel experiments were carried out to investigate the potential causes and it was later discovered to be the propeller whirl flutter instability.

This phenomenon is mainly caused by the interaction of the propeller blades with the airflow and can lead to divergent vibrations and eventually to the loss of the structural integrity. Several factors such as the propeller geometry, propeller and engine inertial properties, damping and rotation speed affect the whirl flutter stability characteristic of the propeller aircraft [Reed 1966, Cercdle 2017]. A thorough examination of these parameters is of great concern for engineers who seek for a whirl flutter free design.

With the emergence of the novel electric-propeller aircraft designs, this phenomenon, which is critical for more compact and lighter electric-powered engines, has become once again a focus of attention [Hoover et al. 2018]. To analyze whirl flutter, various methods that are mainly based on the frequency-domain approach and time-domain approach have been developed so far. Among them is MSC NASTRAN which utilizes a frequency-domain approach based on Doublet-Lattice Method and is used as a de facto tool in the industry for aeroelastic applications. Rose and Rodden in 1989 developed a method and incorporated it in MSC NASTRAN through DMAP procedure to solve the whirl flutter of propeller aircraft. Based on this approach we, in this study, present a numerical investigation on predicting the whirl flutter boundary. Two cases namely, D-1807 propeller and BAH wing/engine configurations were selected and analyzed using MSC NASTRAN. The propeller aerodynamic matrices were

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computed through a FORTRAN code *propf* which was provided along with the NASTRAN installation. Overall, MSC NASTRAN software in whirl flutter analysis is presented as a practical and effective tool that could be also be utilized for distributed electric propulsion aircraft.

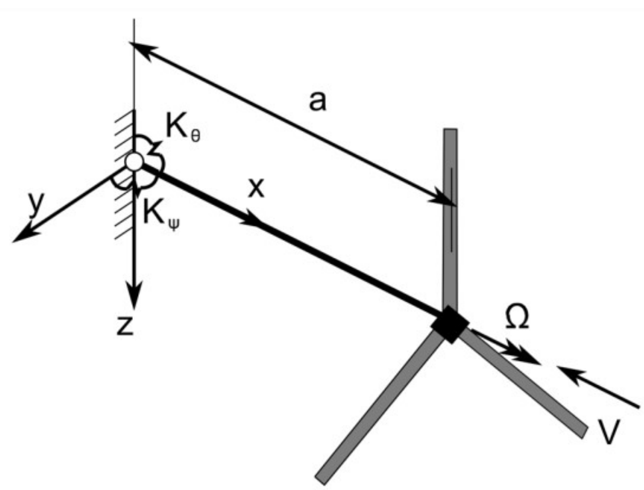
ANALYSIS

To determine the flutter boundaries, whirl flutter analyses of two example cases, D-1807 propeller and BAH wing/engine configurations, were performed and stability boundaries of MSC NASTRAN software using a propeller preparation program.

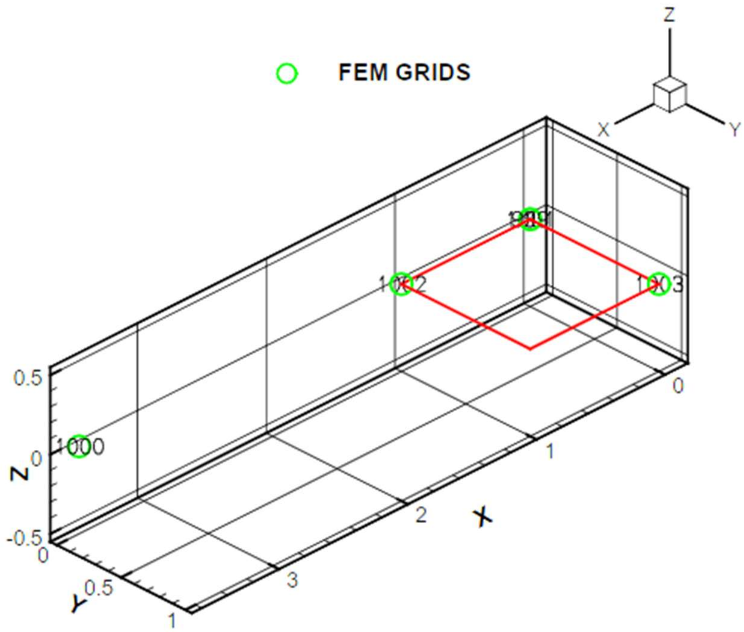
NASA D-1807 propeller

As a two-dimensional model, a sample study the D-1807 propeller [Rose and Rodden, 1989] was selected. This case study was analyzed using MSC NASTRAN program. The configuration is an ideal model to study the propeller-engine whirl instability. We note that although this model is very useful for examining the effects of various system parameters on whirl instability, it is not suitable for demonstrating the effects that occur in a real aircraft structure.

Figure 1(a) shows the sketch of this model which consists of a propeller that is assumed to be rigid and an engine that is elastically mounted from the pivot point. The system has two degrees of freedom, which are the pitch and yaw angular displacements, similar to those given in Reed and Bland's [Reed and Bland 1945] analytical model. Next to this figure, Figure 1(b) is displayed to present the aeroelastic model of the propeller-engine system. This figure is taken from the manual of ZAERO [Zaero 2017], which is an aeroelastic analysis tool that uses a similar approach to MSC NASTRAN. This program has a solver called ZWHIRL developed for whirl flutter stability analysis.



(a)



(b)

Figure 1. (a) Sketch of propeller-engine model [Koch 2021], (b) Aeroelastic model of D-1807 propeller [Zaero 2017]

As illustrated in both Figures 1(a) and 1(b), the model presents a highly idealized propeller-engine system. In order to represent engine mass and propeller mass CONM2 card, and the elastic spring's connections CELAS2 card were used. The geometric specifications of the 4 bladed NASA TN D-1807 propeller configuration had a blade with a root chord of c_r=4.375 in, a polar moment of inertia of I_x=0.10269 lb.in s^2, propeller radius of R=10.1256 in. In order to model the idealized rigid propeller structure, the point representing the propeller hub and the pivot point where the engine was mounted, were connected to each other by a rigid rod, handled by RBAR card in NASTRAN. An additional local coordinate system was also defined for the propeller axis to define the rotation axis. Following the structural modeling, a dummy aerodynamic panel using CAERO1 card was created and the interpolation between the structural and aerodynamic models was established using a SPLINE2 card. All in all, the propeller whirl instability boundaries were determined under the action of SOL75.

The results of the whirl stability analysis are plotted in the next figures. Figure 2 demonstrates whirl stability boundaries for D-1807 propeller-engine system. In this figure, the orange line corresponding to the backward whirl mode is the stability boundary. The region to the left of this line is regarded as the stable region, while the one to the right of this line is the unstable region. Also, as seen, the unstable mode is found as a backward whirl mode, while the forward whirl mode is stable, which is always the case when the propellers are assumed to be rigid [Reed 1966]. The critical speed at which whirl stability onset occurs is found at 105 ft/s.

Figure 3 displays the frequency results plotted against speed for D-1807 configuration. The frequency corresponding to critical backward whirl mode is found as approximately 7 Hz.

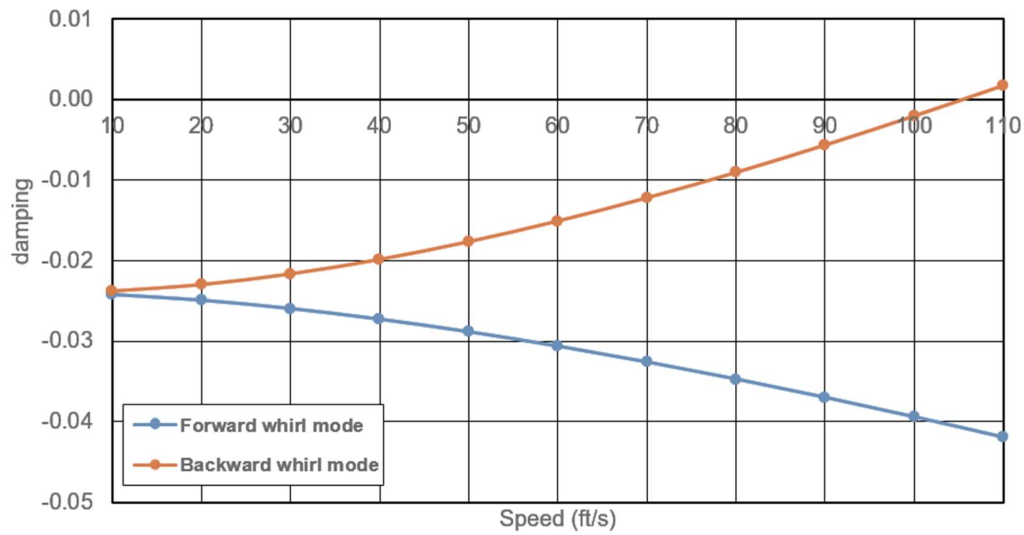


Figure 2. Damping versus speed plots for D-1807 configuration

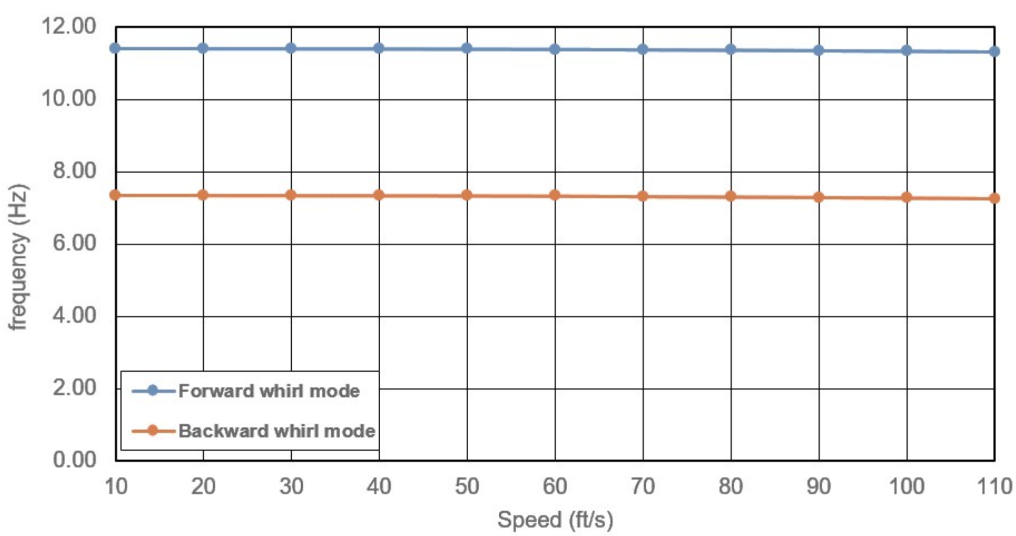


Figure 3. Frequency versus speed plots for D-1807 configuration

BAH Wing/Engine Configuration

In the next set of analysis, a wing/engine configuration was taken into account. In this configuration wing was modeled as an elastic lifting surface, while propeller was rigid and engine was elastically mounted to the wing. This wing configuration also known as BAH wing/engine is sketched in Figure 4. Whirl stability analysis was conducted for this configuration using similar structural and aerodynamic cards and analysis procedures to D-1807 propeller.

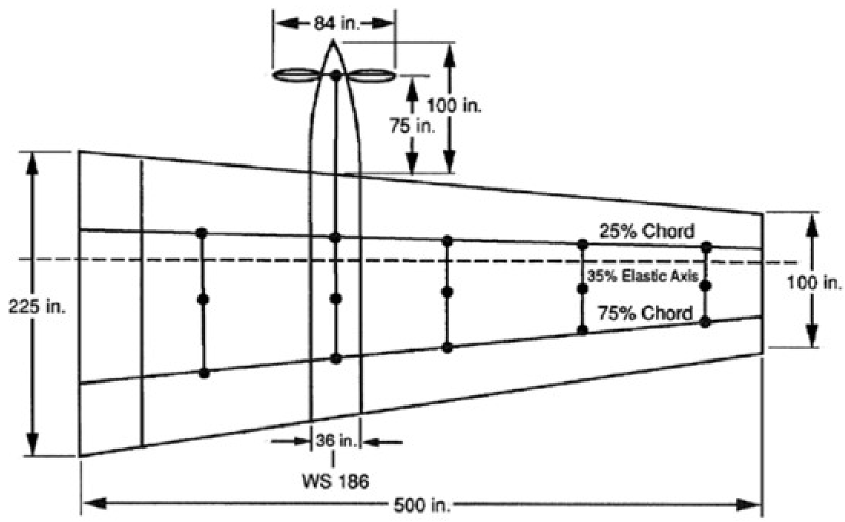
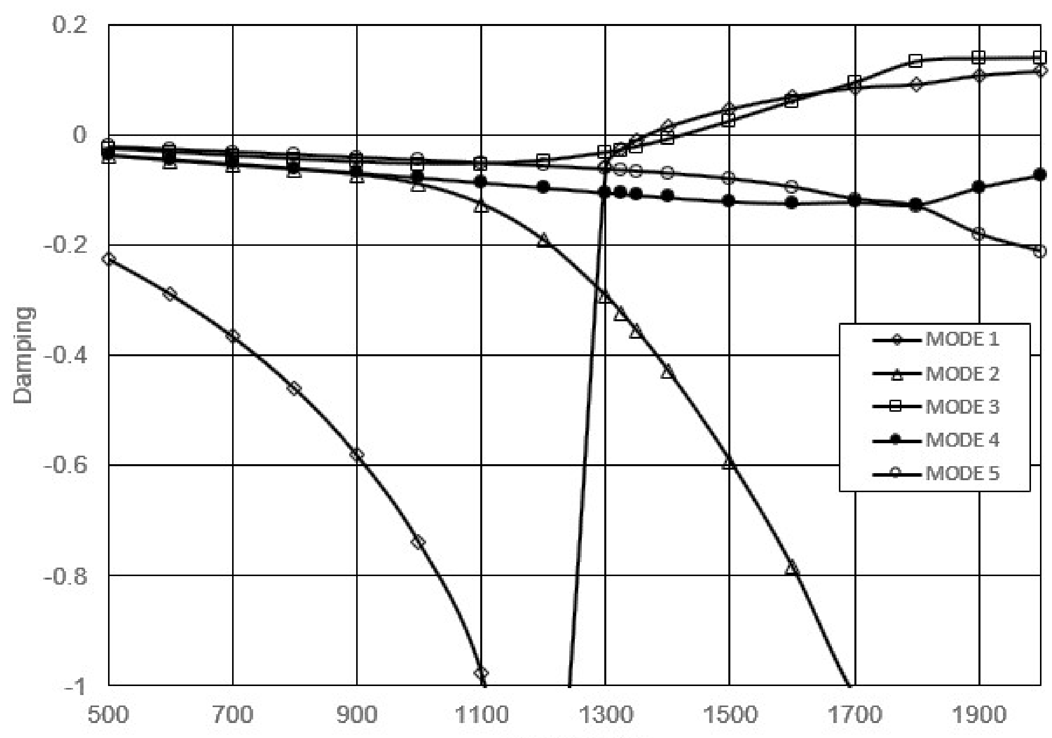
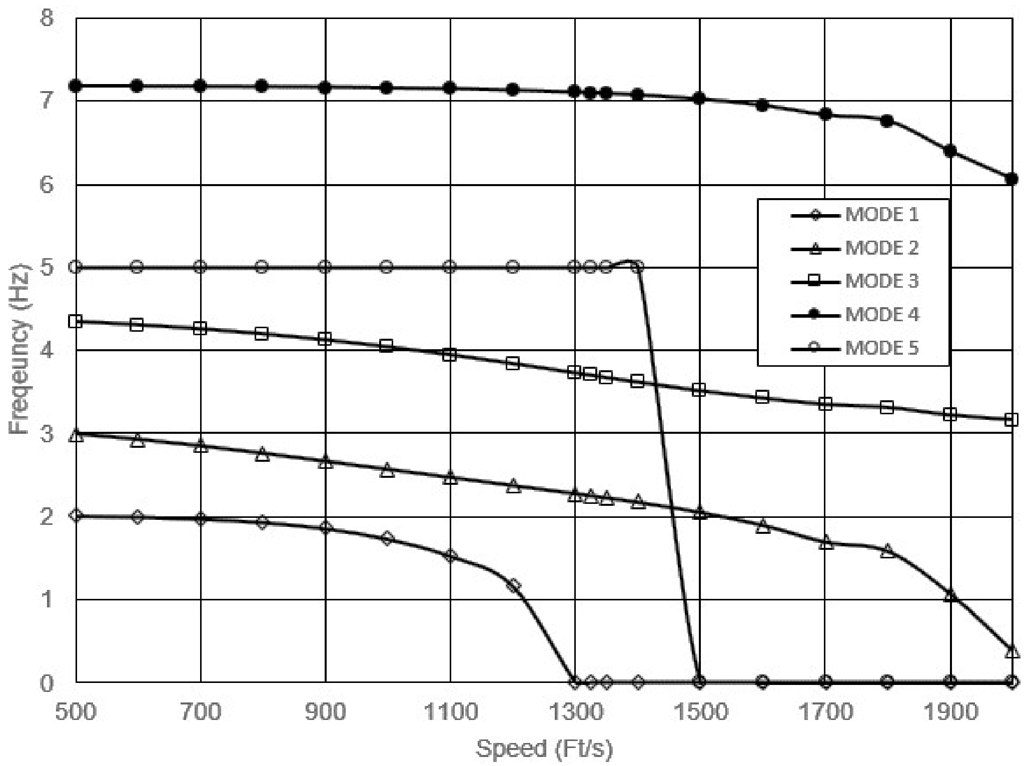


Figure 4. BAH wing/engine configuration [MSC NASTRAN 2018]

The whirl stability analysis of the BAH wing-engine has been conducted using MSC NASTRAN program. As mentioned earlier, for the preparation of the propeller aerodynamic matrices, *propf* FORTRAN program has been utilized.



(a)



(b)

Figure 5. Whirl flutter boundaries of BAH wing/engine configuration

Figure 5(a) illustrates the stability boundaries of BAH wing/engine. As seen from this figure, the whirl flutter was found in the third mode at 1450 ft/s, while the divergence speed is found at 1375 ft/s. The frequency versus speed graph is plotted in Figure 5 (b). As seen from these figures for the first and fifth modes only divergence was observed. The frequency branches of the second and third modes tend to behave as a single branch near the region of onset of flutter.

CONCLUSION

Propeller whirl flutter instability imposes restrictions on the flight envelope of the aircraft and thus must be eliminated to ensure safety and structural integrity of the aircraft. In this study, we present a methodology to predict the whirl stability boundaries of propeller aircrafts. For this purpose, two cases namely the D-1807 propeller and the BAH wing/engine configurations were analyzed using the MSC NASTRAN software. The propeller aerodynamic matrices were obtained using a preprocessor program which is included in the NASTRAN. Overall, the effectiveness of MSC NASTRAN in predicting whirl instability is assessed. This methodology could especially be promising for electric-powered aircraft that have gained popularity over the recent years and are susceptible to whirl flutter instability.

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