WAVE PROPAGATION IN AN AIRCRAFT WING SLAT FOR DE-ICING PURPOSES

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ABSTRACT

Ice accretions on aircraft lifting surfaces must be removed in flight to avoid catastrophic accidents. Conventionally, this is done effectively but inefficiently by bleeding hot air from the engines prompting a number of low energy approaches to be explored that use high amplitude shock or vibration. One recently proposed method, which has so far been successfully implemented for a beam, generates a shock response at a target position by focusing elastic waves in time and space from a single actuator. However, prior knowledge of the dispersion characteristics of such waves is required.

In order to extend the applicability of the technique, this paper aims to predict the dispersion curves of waves propagating along the leading edge of a Boeing 737 wing slat. A semi-analytical finite element (SAFE) model is implemented in Comsol Multiphysics software. By assuming a spatially harmonic displacement field in the direction of propagation only the 2-D cross section of the waveguide needs to be meshed.

Dispersion curves are presented for the leading edge portion of the erosion shield under several assumed sets of boundary conditions. The dispersion curves are compared with measured results from laboratory tests conducted on the real wing slat and found to be in good qualitative agreement. The model will be further developed to predict interfacial shear stresses between the wing skin and accreted ice under transient loading.

1 INTRODUCTION

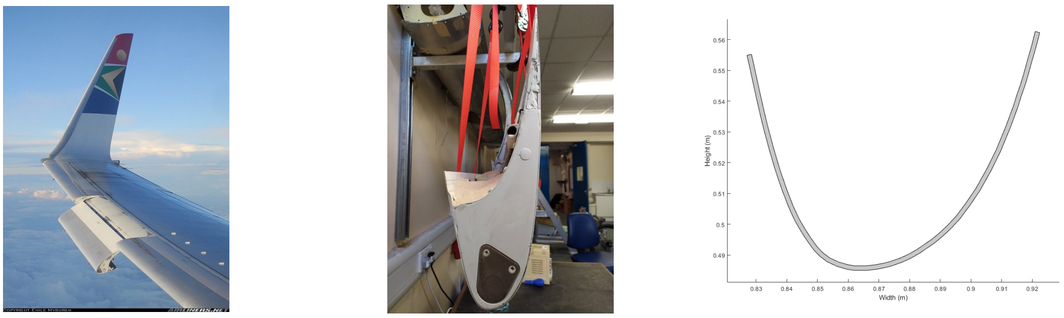
Wings and other aircraft lifting surfaces must be kept free from ice to maintain aerodynamic performance and controllability. Traditional methods of ice protection depend on aircraft size and include pneumatic de-icing boots, electro-thermal systems, glycol based fluid and bleed air. Each has its own drawbacks such as weight, cost, complexity, unreliability, high maintenance or power consumption. To overcome these difficulties a number of electromechanical de-icing concepts have been proposed over the years. They are low-energy solutions that use mechanical pulses or vibrations to break the bond between the ice accretion and the structure. An overview of the state-of-the-art can be found in [1].

Ultrasonic vibration methods, specifically for rotorcraft, have been pioneered by researchers from Pennsylvania State University, and these activities are summarised in [2]. The main limitations relate to the capacity of piezoelectric actuators to deliver sufficient force and, relatedly, the need to drive them at resonance causing them to heat up and crack. To circumvent this problem Waters proposed the use of transient, chirp excitations which achieve amplification through wave focussing instead of resonance [3]. This approach has been shown capable of delaminating an ice substitute from a beam [4]. Extension of this method to realistic wing structures requires prior knowledge of free wave propagation along the wing leading edge where ice accumulates in order to negate and even exploit the effects of wave dispersion.

For structures with complicated cross-sections dispersion curves must be found numerically. A method which is readily applicable to uniform waveguides is the semi analytical finite element (SAFE) method. In this paper, the SAFE method is used to model the leading edge of a Boeing 737 wing slat, the results of which are partially validated through laboratory experiments.

2 FREE WAVE PROPAGATION MODEL OF WING SLAT

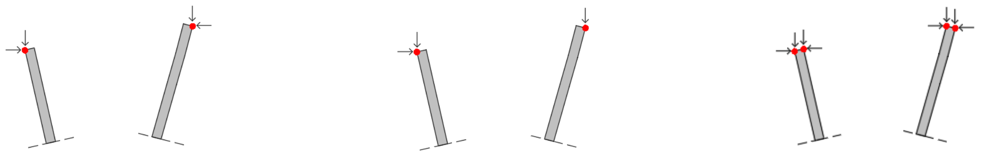
The SAFE method assumes uniformity along the length of the waveguide. Whilst the Boeing 737 wing slat shown in Figure 1a-1b has periodic ribs these extend only as far as the forward spar, and so the aluminium erosion shield is modelled approximately as a uniform curved plate, as shown in Figure 1c. Its cross-section is approximately 80 by 100 mm with a skin thickness of 1.5 mm. Three different models were considered, with hinged, simply supported and clamped boundary conditions, as shown in Figure 2. In addition, three different meshes have been considered for each model: 45 linear elements, 180 linear elements and 180 quadratic elements.



(a) (b) (c)

Figure 1: Boeing 737 wing slat: (a) leading edge slats on a Boeing 737. Image with kind permission of Emile Myburgh, (b) cross-section of the wing slat and (c) cross-section of the model.

The numerical results were obtained using COMSOL Multiphysics finite element software [5] and implementing the SAFE problem through its *Coefficient Form PDE Interface* as proposed in [6]. Dispersion curves in the form of wavenumber against frequency were obtained from the solutions of the eigenvalue problem yielded by the SAFE method for a set of frequencies from 0 to 10 kHz. The first four cut-off frequencies for the corresponding three models and three mesh configurations are reported in Table 1. Mesh convergence has not yet been achieved due to computational limitations, and a finer mesh will be required for future studies.



(a) Hinged (b) Simply supported (c) Clamped

Figure 2: Boundary conditions of the wing slat models: (a) hinged, (b) simply supported, and (c) clamped.

Boundary condition	Mesh	Cut-off frequencies (Hz)			
		1^{st}	2^{nd}	3^{rd}	4^{th}
Hinged	45 linear elements	513.13	1662.68	2935.83	4788.86
	180 linear elements	337.82	1100.31	1962.59	3226.41
	180 quadratic elements	239.18	788.21	1445.34	2429.59
Simply supported	45 linear elements	125.20	830.87	1922.02	3282.33
	180 linear elements	87.99	551.16	1256.68	2165.85
	180 quadratic elements	69.38	394.46	882.07	1551.95
Clamped	45 linear elements	832.48	2329.72	3961.79	5951.52
	180 linear elements	558.37	1541.84	2621.96	3998.57
	180 quadratic elements	418.46	1115.88	1901.71	2994.22

Table 1: First four cut-off frequencies of the wing slat models discretised by three different meshes.

3 EXPERIMENTAL VALIDATION

Vibration measurements were conducted on the 3.5 m long wing slat which was suspended by ratchet straps. One end was buried in a box of dry sand of tapered depth to provide some reduction of reflections. The wing slat was excited using a micro impulse hammer (PCB 086E80) and the acceleration was measured with a miniature accelerometer (PCB 352C22). Transfer function measurements were then acquired using a Data Physics Quattro spectrum analyser. In total, 26 accelerance transfer functions were measured, in the centre section of the wing to minimise contamination by near fields, with a spatial array of length 0.6 m and a sensor spacing of 0.025 m. The measurements were then repeated at a different chordwise position, slightly behind the stagnation point, to improve the possibility of sensing all wave types. Dispersion curves were then estimated from the transfer functions using the correlation method proposed in [7].

Figure 3 shows the estimated dispersion curves from the combined sets of transfer functions. Multiple branches are apparent corresponding to different wave types. Also shown are the predicted results from the SAFE model with 180 linear elements and simply supported boundary conditions. Whilst the mesh is not fully converged, these boundary conditions best replicate the measured cut-off frequencies at around 500 Hz, 1300 Hz, 3000 Hz and 6600 Hz.

4 CONCLUSIONS

A SAFE model of the leading edge of an aircraft wing slat has been implemented using commercial software to obtain dispersion curves of elastic propagating waves. There is qualitative agreement with measurements on a real slat from a Boeing 737 aircraft, notwithstanding the limited extent of the model.

In future work, the model will be extended to compute the forced response due to a chirp-like input waveform chosen to focus waves at a target position. An accretion will be added enabling interfacial stresses between the wing skin and accretion to be predicted.

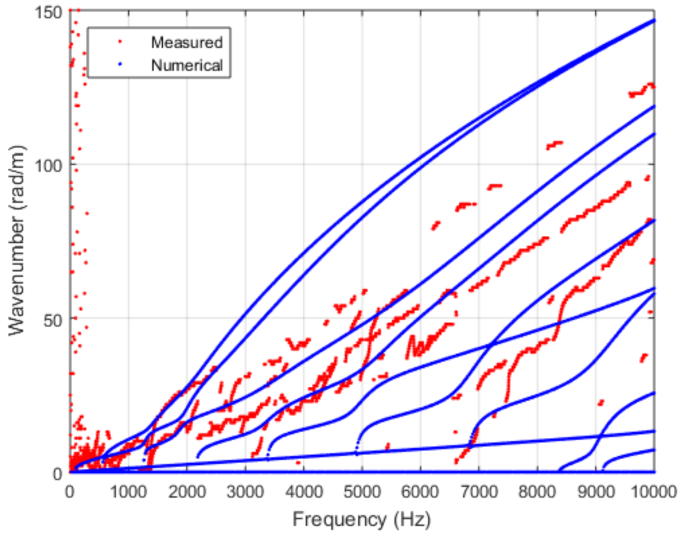


Figure 3: Measured and numerical dispersion curves for the simply supported wing slat model discretised by 180 linear elements.

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