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Development and validation of a set-up to measure the transferred multi-axial impact momentum of a bird strike on a booster vane

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ABSTRACT

Reaction force has always been one of the main characterization parameters for impact events. Today, a set of force transducers are a common and valuable tool to measure reaction forces. But the force signals are often influenced by vibrations of the supporting structures. Many other attempts were already taken in the past to use other methods to measure force, such as ballistic pendulums, Hopkinson bars, etc., all having their advantages and disadvantages. In this work, a multi-axial force measurement tool is developed to serve in a test campaign of bird strike experiments on booster vanes. The idea is to give some well-chosen mass three rotational degrees of freedom and acquire the transferred rotational momentum from an optical measurement, which is a direct measure for the impact force. The tool is validated experimentally and numerically using a simplified steel vane.

1. Introduction

Certification by analysis is a hot topic these days. But, a lot of research is still required to be able to prove that numerical methods are fully capable for simulating bird strike. The work described in this paper is part of the European FP7 project *E-Break* or *Engine BREAK through Components and Subsystems*, where the key jet engine subsystem technologies are further developed to incorporate in ultra-high overall pressure ratio (OPR) and high bypass ratio (BPR) engines. In this project, a small task is devoted to the development of a numerical model that is able to validate the design rules of the booster vane in terms of bird strike robustness and investigate the possibilities of Variable Stator Vane (VSV) systems.

The validation of the numerical models for bird strike requires quantitative measurements. Strain gauges on one hand can tell something about local deformations at discrete points on a structure. The measurement of residual energy after impact [1] and reaction forces on the other hand are valuable parameters that give an idea of the global performance. Optical measurements can also provide full field displacement and strain fields. The optical view however is often disturbed in bird strike experiments, and a stereo set-up of high-speed cameras dedicated to the measurement would be required. The measurement of reaction forces therefore remains one of the primary parameters for characterizing the impact event. Several techniques were already successfully used, from ballistic pendulums to Hopkinson bars and load cells and methods in between.

The oldest technique is the ballistic pendulum. The original idea dates back from the reference work of Robins in 1742 [2], where it was used to measure the momentum of a bullet. An application of the pendulum in bird strike research can be found in the work of Bertke etal. [3], where a 5 wire pendulum was used to measure the total transferred momentum of a bird strike on titanium blades. They calculated the transferred momentum from the chord length and the oscillation period after impact.

Hopkinson introduced a first version of the Hopkinson bar in 1914 [4], which was basically an advanced version of the ballistic pendulum. Hopkinson proposed a co-axial system of two bars, where the second bar is suspended and able to trap a part of the momentum depending on its length. The strain waves in the first bar however can, in the ideal case, be directly related to the impact force, as was tried in the reference works on bird strike from Barber etal. [5] and Wilbeck [6], in which forces were measured of bird strike on flat and inclined surfaces using a Hopkinson bar set-up. But they had to integrate the momentum signals. Because of the high frequencies that were dispersed due to the large diameters of the bars, exact force time signals could not be obtained. A more recent attempt was taken in the work of Seidt [7].

In the work of Allcock [8], the targets were attached to a set of calibrated beams. The deflection of the target was measured, from which the impact force was derived. In [9], the targets were able to move in the direction of impact, from which the impact force could be derived directly.

To test bigger and complex full scale structures such as leading edge wings, flaps or windshields and to acquire force time signals, a set of load cells or instrumented links are often used to measure the

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reaction force at discrete points [10–18]. The problem with load cells is that the force signal is often influenced by vibrations of the supporting structure. Numerical simulations are capable of incorporating a part of the boundary conditions, but the interpretation of the signals is nevertheless not straightforward.

Prior to the booster vane experiments that were to be executed in the course of this project, the purpose was to develop a tool able to measure reaction forces in multiple directions. This is achieved by allowing movement of the set-up, which has the advantage to decouple the experiment from the environment to some extent and to guarantee safety. More specific, three rotational degrees of freedom are given to a well-chosen mass to acquire the transferred rotational momentum, which is an idea that originates from the work of Premont etal. [19] and Steinhagen etal. [20]. Premont and Steinhagen mounted fan blades onto a rigid object that is able to pivot around one point, and measured the transferred momentum around three axes using accelerometers.

Contrary to the work of Premont and Steinhagen, the set-up onto which the vane fixtures are mounted is more compact, reducing the influence of Eigen frequencies of the force measurement tool. Also, the momentum in this work is derived optically from the images of one high speed camera (HSC). The advantage above any kind of sensor, is the fact that it is per definition a non-contact method: no wires that can detach during movement, no triboelectric effect on the wires, no resonance frequencies, electrical current leakage, etc. Contrary to stereo vision techniques, one camera can be used to record other valuable aspects of the experiment. One HSC is already necessary any way to acquire the horizontal offset of the bird.

A so-called cone structure was designed onto which multiple vane configurations can be mounted. To verify the set-up and to have an intermediate step between the initial calibration experiments [1] and the booster vane experiments, a stiff steel vane was used as target object. This paper will introduce the cone as the tool to allow the rotational movement. The different steps necessary to derive the momentum of the cone will be explained in detail. Finally, some results will be shown as well as a comparison with a numerical model, using SPH modelling for the bird.

In the next section, the test set-up to launch the birds and the steel vane will be introduced. In Section 3, the main principle of the force measurement with the cone will be explained. Section 4 contains the actual derivation of the rotational momentum. The next sections contain the results of some experiments, a comparison with simulations and finally a conclusion.

2. Test set-up

2.1. Ugent bird strike test set-up

The experiments were performed on the Ghent University bird strike set-up (Fig. 1). The set-up is capable of shooting birds up to 42 kJ. Birds can be launched with a weight of maximum 4 lb (according to the regulations [21]) at speeds up to 250 m/s. At the beginning of each experiment, a projectile called a sabot is filled with foam in accordance to the desired shape, after which gelatin is moulded into the acquired foam shape. The sabot is mounted in front of a pressure vessel and released at the required pressure. After the release trigger, the sabot launches through a 3 m long barrel and strips off from the bird in the stripper chamber using a cone shaped stripper, after which the stripped bird flies into the test chamber (blue chamber) and impacts on the required target. Before each experiment, the test chamber is evacuated up to 0.2 bar absolute pressure to be able to perform precise velocity measurements. Three lasers with corresponding photodiodes are mounted on opposite sides of the test chamber. The subsequent voltage drop of the photodiodes recorded with a Gen5i oscilloscope makes it possible to determine the speed.

2.2. Target: steel vane

The set-up to measure the transferred rotational momentum will be tested and validated using a simplified steel vane (Fig. 2). Tests on the actual booster vanes cannot be disclosed. The simplified steel vane consists of a V-shaped steel bar welded to a plate. The holes in the plate will be used to mount the vane to the cone structure. Making a (construction steel) vane identical to the Titanium booster vanes is almost impossible due to the difference in yield strength and stiffness. Two strain gauges are applied at a location that does not get hit by the bird. The strain gauges are further referred to as the strain gauge on the back and on the left side of the vane (Fig. 2).

The steel vane will serve as an intermediate step between the initial calibration experiments on rigid targets [1] and the experiments

Fig. 1. Ghent University bird strike test set-up: a sabot with a gelatine bird (top left), the pressure vessel (bottom left) and the stripper and test chamber (right).