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Review

Application of ultrasound for the estimation of flight velocity direction on an aircraft fuselage

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ABSTRACT

A flush mounted ultrasound device is potentially of interest for the non-intrusive measurement of the velocity field around a moving body.

Ultrasound sending and receiving transducers might combine in one technique that could determine certain parameters of flow direction as, for example, around the fuselage of an aircraft in flight.

The study reported here focused on the measurement and the prediction of times of flight in the configuration of a flat wall surrounded by a turbulent boundary layer. The presence of sheared flow and a turbulent boundary layer affects the propagation of acoustic waves.

Time of flight was first estimated by a simplified model involving the convection effect and ignoring the shear layer.

A numerical model based on the ray theory was also developed to take into account the propagation effect of the boundary layer. Indeed, the approximation of geometric acoustics was valid for high frequencies.

In the first part, a comparison is presented to show that both approaches demonstrated similar trends at low Mach numbers. However, experiments conducted in a wind tunnel up to Mach 0.15 showed that the measurements were in better agreement with the estimates provided by ray theory.

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1. Introduction

In the field of aeronautics, awareness of the parameters related to airflow velocity, such as those linking the flow direction and the aircraft, or static and total pressure, is essential for an aircraft pilot because these parameters are directly linked to the lift and drag of an aircraft during flight. Innovative and efficient techniques have therefore already been established in the aircraft industry to measure these parameters. Anemometers, Venturi pipes and pressure probes are now directly mounted on aircraft fuselages to inform the pilot of the flight conditions. However, such measuring devices protrude above the fuselage, and one limitation of this specific feature is that measuring devices need to be regularly reheated in order to combat adverse environmental conditions. They are therefore sometimes difficult to install or to supply with electricity [1].

There is thus a need for new techniques to measure airflow velocity. Measurement of time of flight between ultrasound sending and receiving transducers is one technique that could determine certain parameters of the velocity flow around the fuselage of an aircraft in flight. One advantage of this type of technique is that the system could be flush to an aircraft surface.

Time delay measurement is already widely used in various domains such as medical imaging, meteorology, flow meter techniques, (Ligneul and Hocquet [2] and Raisutis [3]), and aeronautics. For instance, Simecsol has created a prototype able to measure the direction and velocity of wind by means of multiple transducers [4]. In the biomedical field, ZEBRIS CMS-HS is a kinematic analysis system able to determine the joint movement of horses, using time delay measurements between sensors located on orthopedic mounts [5]. Measurement of time delays can sometimes be used to determine distance of travel between sensors, (Srinivasan et al. [6]), where times of flight are measured and analyzed for various acoustic sources.

The aim of this study was to develop an ultrasound probe able to reach high velocities in air flight conditions. In this kind of application, the time of flight of a pulse of sound as it travels from an emitter to a receiver transducer is modified in relation to the direction of the flow by the path in the boundary layer and in the free stream flow over a flat surface. Prediction of this time of flight can be evaluated first by a very simplified model of propagation based on the convection of sound. This model does not take into account the boundary layer effects. A numerical tool based on geometric acoustics is therefore also used to provide a more realistic estimation of the time delays. We present below experimental results obtained with a prototype of an experimental probe that uses propagation delays between several airborne ultrasound transducers flush to the system. First, the experimental device and the facilities where it was tested are presented. Experimental time delay results, obtained in an anechoic wind tunnel, are then compared with numerical results simulated by geometric acoustics. The results are also compared with the simplified model of propagation that can match when the boundary layer effects are not predominant.

2. Experimental set-up

2.1. Experimental device

A system comprising three fixed piezoelectric transducers (one transmitter located in the center and two receivers) was manufactured (Fig. 1) in which emitter and receivers are separated by 55 mm. Transducers with weak directivity (beam angle of 80°) operating at 40 kHz are mounted on a brass plate in order to be flush with the plate. The plate is mounted on a goniometer so that the angle α between the transducer line and the direction of the air stream U_∞, can be chosen accurately. Time delays can be measured either between the downstream and upstream transducers (R_1 and R_2) or between the central emitter and a receiver. Smith and Whale developed a similar device, able to measure free-stream velocity and boundary layer displacement thickness in airflow [7].

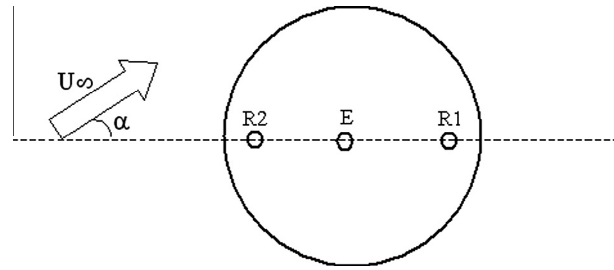

Fig. 1. Diagram of system.

2.2. Characterization of turbulence in anechoic wind tunnel

The prototype was tested in an anechoic Eiffel-type wind tunnel (EOLE, in CEAT, Poitiers), which avoids parietal reflections and reverberation effects during measurements. This facility has been used in several studies of acoustic propagation in the presence of flow, such as [8,9].

The test room dimensions are 2.80 m × 3.80 m × 3.00 m (Fig. 2a). The free field condition is obtained for acoustic frequencies higher than 250 Hz. The nozzle exit, with a square cross-section of 0.46 m × 0.46 m, is connected to the collector by a plywood plate (Fig. 2b).

The maximum wind velocity in the tunnel was 51 m/s, *i.e.* Mach 0.15, measured independently of our system using a Pitot probe. The aerodynamic characteristics of the tunnel were first determined by measuring the boundary layer at different positions on the flat surface of the anechoic chamber for different Mach numbers. The best location for the transducer system, flush-mounted in the plywood plate, was thus chosen in relation to the boundary layer measurements.

Boundary layer thickness and turbulence intensity were measured using a hot wire anemometer. Turbulence intensity was defined as the ratio between the root mean square of the velocity fluctuation and the average velocity at a local point. Assuming the Reynolds decomposition

$$u = \overline{U} + u'$$

where U is the mean velocity and u' the turbulence fluctuation, the turbulence intensity is

$$\tau = \frac{\sigma_{u'}}{\overline{U}}$$

where

$$\sigma_{u'}^2 = (u' - \overline{U})_t^2$$

with the expression $\langle\ \rangle_t$ which represents the temporal mean of the fluctuations.

The profiles obtained are reported at Mach 0.15 in Figs. 3 and 4, respectively. In the following, the origin of the locations is taken at the nozzle exit.

As shown in Figs. 3 and 4, the characteristics of the airflow profiles depended on the distance from the nozzle exit: the boundary layer became thicker in the downstream direction and the turbulence intensity also increased (curves at 722.5 mm, Figs. 3 and 4).