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Experimental characterization of the transonic test section flow in a Ludwieg tube

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A R T I C L E   I N F O

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A B S T R A C T

A new Ludwieg tube for transonic testing has been put into operation. For this, an existing shock tube has been modified to a Ludwieg tube. The ideal operating principle is described by theory and corresponding theoretical values are compared to experimental ones. Pressure histories as well as test section flow visualization demonstrate a better performance concerning flow quality and testing time compared to the former shock tube. Static as well as total pressure measurements have been performed within the test section. Pitot rake measurements show the homogeneity of the test section flow field. Additional boundary layer profile measurements give evidence of the temporal growth of the test section wall boundary layer. These results are compared with theoretical ones deduced from a theoretical approach for a boundary layer behind an expansion wave. Both, boundary layer and Pitot rake measurements allow to discuss the influence of a turbulent boundary layer on these measurements. Cookie cutters at the entrance to the test section act as boundary layer bleed which partially avoid the entering of the tube wall boundary layer into the test section. Their influence on the test section flow is discussed as well.

1. Introduction

During the last years, interest in transonic flows has increased in order to improve the flow quality of civil airplanes at subsonic speeds. The flow pattern in the transonic regime around an airfoil differs significantly from the flow at subsonic or supersonic conditions. In this flow region many different interactions of weak and strong shock waves with the boundary layer exist. For a certain Mach number range, these interactions are influenced by traveling pressure waves along the airfoil. So far, comprehensive investigations of pressure waves in compressible subsonic and transonic flow were performed in the transonic shock tube (STK) at the Shock Wave Laboratory (SWL) of RWTH Aachen University.

For a modification of the existing shock tube, the Ludwieg tube wind tunnel concept was chosen. The goal of the modification was to increase the testing time and to improve the flow quality. In Ludwieg tubes, the flow is initiated by an expansion wave. Due to this initialization, interactions with wind tunnel models are significantly weaker. Therefore, Ludwieg tubes deliver a high flow quality associated with low turbulence levels in comparison to other impulse facilities. In 1955, the wind tunnel concept of a Ludwieg tube was suggested by Ludwieg [6]. This facility was designed as a low cost alternative for subsonic and transonic testing at relatively high Reynolds numbers [6]. It has been proven that the Ludwieg tube is more cost effective than a blowdown tunnel of similar size [1]. Ludwieg tubes are equipped with fast opening valves or bursting diaphragms to generate an expansion wave to accelerate the high-pressure gas stored within a charge tube. Numerous Ludwieg tube facilities are operated around the world due to the low costs of construction and operation [10]. The high flow quality in combination with high Reynolds numbers and reasonable long testing times (100–1000 ms) are the main reasons for the frequent application of this type of facilities.

In 1969, a Ludwieg tube with the largest test section was built at NASA Marshall Space Flight Center [4]. The circular test section has an inner diameter of 813 mm. The charge tube has a diameter of 132 cm and a length of 115 m and can be pressurized up to a maximum pressure of $48 \cdot 10^5$ Pa. The facility can operate at supersonic Mach numbers of 1.4, 1.7 and 2.0 by using three supersonic nozzles. Subsonic Mach numbers from 0.25 to 0.77 can be achieved as well by inserting a sonic nozzle. Two different Ludwieg tubes have been built at DLR Göttingen. The hypersonic Ludwieg tube (RWG) has a charge tube length of 80 m. The facility covers a Mach number range from 3 to 7 by using six different nozzles. The unit Reynolds number ranges from 5 to 80 million per meter. The flow is initiated by a fast opening valve. The RWG has a cross-section of 0.34×0.34 m^2 for Mach number $M = 2$ and 0.5×0.5 m^2 for the Mach numbers 3 and 4. For higher Mach numbers a circular

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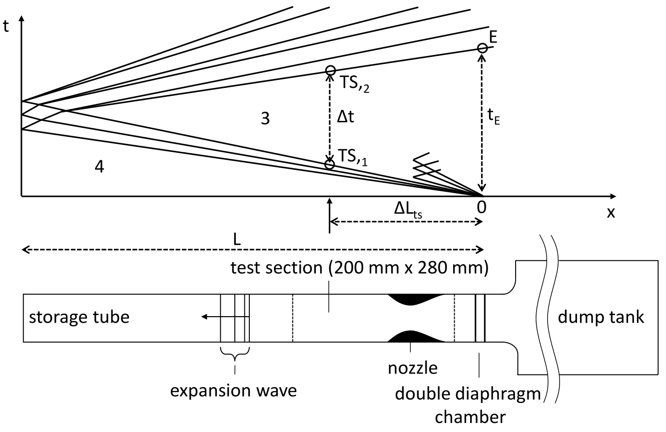

Fig. 1. Wave diagram of the present Ludwieg tube (LTK).

cross section with 0.5 m diameter is used. This facility allows a testing time up to 400 ms. DLR Göttingen also operates another Ludwieg tube based on the same principle, the Cryogenic Ludwieg tube (KRG). For this facility the charge tube and therewith the initial temperature of the test gas can be cooled down to 100 K. The KRG provides Mach numbers from 0.25 to 1 and due to the cryogenic technology Reynolds numbers up to 50×10^6 for an airfoil model of 150 mm chord length. The large charge tube length of 130 m allows a testing time of 1 s. The charge tube has an inner diameter of 0.8 m. The KRG features a rectangular test section of 400 mm width, 350 mm height and 2000 mm length. Furthermore, the KRG is equipped with an adaptive wall test section which can be adjusted in order to test larger models. Thereby, the Mach number also can be extended to about 1.5 by using a part of the wall as an extension of the nozzle [7]. Moreover, an additional valve is used for Mach number control.

This paper describes the modification of an existing transonic shock tube to a transonic Ludwieg tube in order to achieve superior flow quality and to increase the testing time significantly. The modified facility can be operated as a shock tube as well as a Ludwieg tube for transonic testing, which requires only minor changes. In the following, the tunnel calibration and boundary-layer effects of the Ludwieg tube flow will be presented and analyzed.

2. Facility

Ludwieg tubes consist basically of a long storage tube, a test section, a nozzle and a vacuum tank. A fast acting valve or a bursting diaphragm separates the pressurized part from the evacuated part. In general, Ludwieg tubes allow transonic, supersonic or hypersonic flow conditions. Beside the initial storage tube conditions, the flow condition of a Ludwieg tube depends on the location of the nozzle with respect to the test section. Therefore, the test section can be placed up- or downstream of the nozzle location.

2.1. Operating principle

The gas dynamic process of the chosen transonic Ludwieg tube configuration is explained in Fig. 1. A bursting diaphragm separates a storage tube, followed by a test section, which is connected to a nozzle from a vacuum tank. Hence the test section, the nozzle and the storage tube belong to the pressurized parts of the facility. The desired Mach number in the test section is generated by the shown convergent, divergent nozzle (see Fig. 1).

The undisturbed gas upstream of the expansion wave is located in region 4 at the static pressure p_4 and the static temperature T_4. Since the flow velocity in the storage tube is zero, stagnation pressure and temperature correspond to the static values, i.e. $p_{04} = p_4$, $T_{04} = T_4$. Furthermore, region 3 corresponds to the flow conditions downstream of the expansion wave.

A double diaphragm chamber allows a controlled rupture of the diaphragms which starts the flow. The opening process occurs relatively fast and can be regarded as instantaneous [11]. Hence an expansion wave travels upstream into the pressurized region. First, the expansion wave passes the nozzle thereby starting the nozzle flow. After the flow in the nozzle throat reached sonic speed, no more expansion waves are able to pass the nozzle. The part of the expansion wave which already passed the nozzle, travels further upstream into the storage tube and continuously supplies the nozzle with air at constant total temperature and pressure. The nozzle of the Ludwieg tube is installed at the downstream end of test-section (see Fig. 5). As a consequence of this, the cross-sections of the nozzle inlet and outlet are the same, corresponding to the cross section of the test section. The freestream Mach number M_3 can be determined by the area ratio of the sonic throat of the nozzle to the test-section, A^*/A_{TS}.

$$M_3 = \frac{A^*}{A_{TS}}\left[\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M_3^2\right)\right]^{\frac{\gamma+1}{2(\gamma-1)}}. \tag{1}$$

A^* is the sonic throat cross section of the nozzle, A_{TS} is the cross section of the test section and γ is the specific heat ratio. Thus for the present case, the freestream Mach number M_3 is determined by the subsonic solution of Eq. (1). After the expansion wave has reached the end of the storage tube, a reflection of this (see Fig. 1) propagates back towards the test-section. The usable testing time starts after the tail of the expansion wave has passed the test section and ends with the arrival of the reflected expansion wave. During this time period the flow in the test section remains steady as long as viscous effects can be neglected. The flow conditions behind the expansion wave can be described by simple-wave theory for the case of a relatively fast opening of the diaphragm. Therefore, the unsteady expansion wave can be calculated by the usual relation for a right running characteristic [5]:

$$u_3 + \frac{2a_3}{\gamma-1} = \frac{2a_4}{\gamma-1} \tag{2}$$

The ratio of the speed of sound a_4/a_3 then follows by:

$$a_4/a_3 = 1 + \frac{\gamma-1}{2}M_3. \tag{3}$$

The static pressure p_3 behind the expansion wave can be determined by Eq. (3) and by the isentropic relation:

$$p_3 = p_4\left[1+\frac{\gamma-1}{2}M_3\right]^{\frac{-2\gamma}{\gamma-1}}. \tag{4}$$

For subsonic flow, the corresponding Pitot pressure in region 3 is then given by:

$$p_{03} = p_{04}\left[1+\frac{\gamma-1}{2}M_3\right]^{\frac{-2\gamma}{\gamma-1}} \cdot \left[1+\frac{\gamma-1}{2}M_3^2\right]^{\frac{\gamma}{\gamma-1}}. \tag{5}$$

The static temperature T_3 downstream of the expansion wave is determined by

$$T_3 = \left(\frac{a_3}{a_4}\right)^2 T_4 = T_4\left[1+\frac{\gamma-1}{2}M_3\right]^{-2}. \tag{6}$$

Due to the unsteady expansion, the total temperature of the gas does not remain constant over the expansion. The total temperature $T_{03} \neq T_{04}$ can be calculated by using the reformulated energy equation for region 3.

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