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Contributions of Bram Wijnands to Experimental Aeroacoustics, part I: from supersonic jet screech to human voiced sounds production

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From 1956 until 1998, A. P. J. (Bram) Wijnands (1934-2017) has designed, built and run many experimental facilities at Technische Universiteit Eindhoven (TU/e) in collaboration with a.o. L. Poldervaart, G. Vossers, M.E.H. van Dongen and A. Hirschberg. Initially the research on aeroacoustics was inspired by the development of the Concorde supersonic aircraft. Bram carried out spectacular flow visualization on supersonic free jets with rectangular cross-section. This provided unique insight into the jet screech phenomenon. Around 1980, the work shifted to the study of instabilities in natural gas transport systems at low Mach numbers. The role of closed side branches in the drive of self-sustained pulsations was modelled on the basis of his experiments. Quantitative measurements on the aeroacoustic response of pipe discontinuities (pipe termination, expansion of cross section, diaphragms, corrugated pipes) and turbine flow meters were carried out at TU/e and the Laboratoire d'Acoustique de l'Université du Maine (LAUM). Starting around 1988 the study of human snoring at the LAUM and of voiced sound production at TU/e and the Institut de la Communication Parlée (Grenoble) lead to new fundamental insights. Both the work on the aeroacoustics of internal flows (LAUM) and human voiced sound production (Grenoble-INP) is ongoing, using set-ups built, designed or directly inspired by Bram. The paper presents a few highlights of original and recent work.

1 Introduction

A. P. J. (Bram) Wijnands (1934-2017), see Fig.1, started working as a technician at the Eindhoven University of Technology in 1957 when the laboratory for Fluid Dynamics of the faculty of Applied Physics was created. He initially designed and built-up basic facilities such as wind tunnels.

L. Poldervaart has initiated, in collaboration with Bram, the research in Aeroacoustics around 1960. After some work on the thermoacoustics of the Hartmann-Sprenger tube, the research focused on the self-sustained oscillations of large aspect ratios rectangular under-expanded supersonic free jets. This work was inspired by the use of rectangular jet cross-sections in the Concorde supersonic aircraft. Using various flow visualization techniques they obtained high quality stroboscopic measurements that clarified the essential components of the involved feedback loop. This work was published in the form of a movie presented at a conference : https ://www.youtube.com/watch ?v=dJp5m1SDN5c .
This movie was obtained by using a succession of high definition pictures (Fig. 2) taken at accurately determined phases of the oscillation cycle by using a nanolite flash (60 nano-second). This was made possible by the excellent electronic set-up designed and built by Eep van Voorthuijzen. The flow visualisation demonstrates that the sound source in jet screech is induced by the interaction of vortices formed in the shear layers of the under-expanded supersonic jet with a stationary shock. The shock is a result of the global successive expansion-compression cells of the under expanded jet. When placed under anechoic (free-field) conditions this vortex-shock interaction occurs at the third compression shock. The opposite phase of the acoustic waves generated on both sides of the jet is demonstrated by the high quality shadowgraph pictures (Fig. 2). These acoustic wave propagate in the stagnant air surrounding the jet to interact with the sharp edges on both sides of the nozzle outlet. This interaction results into the modulation of the vorticity in the jet shear layers, which can be explained in terms of a Kutta condition (quasi-steady tangential flow separation at the nozzle edge). The hydrodynamic instability of the shear layers results, into the formation of a large coherent vortical structures (vortices), which are convected downstream along the shear layers toward the third shock. This closes the feedback loop responsible for the jet screech oscillation. When plane reflectors are placed normal to the side walls of the nozzle at a quarter of a wavelength based on the screech frequency, the jet oscillation amplitude is dramatically increased and the sound source moves upstream, to the first shock position. The feedback loop amplification has been enhanced. When sound absorbing wedges are placed along the sides of the jet, the feedback loop is interrupted and the jet is stabilised. More expantion-shock cells appear along the jet. Later work determined various oscillation modes of the jet obtained by modifying the acoustical feedback towards the jet
(https ://www.youtube.com/watch ?v=EnlCDOQW7wc).
Among others one observes next to the asymmetric jet oscillation dominating the first observations, a symmetric mode in which vortices are generated simultaneously on both sides of the planar jet. Finally Poldervaart and Wijnands focused on the generation of vortices at the edge of the jet outlet nozzle
(https ://www.youtube.com/watch ?v=lMfb2IRMVuo).
This work was the source of inspiration for the theoretical work of S.W. Rienstra [1], who explained the full significance of the Kutta condition for the aeroacoustic response of subsonic jets. In collaboration with Bram, J.E. Field investigated the aeroacoustics of the interaction of two planar supersonic jets
(https ://www.youtube.com/watch ?v=EV0df7WN4Bg).
This work was presented at a conference [2].

Around 1980, the work on self-sustained flow instabilities in subsonic pipe flows as found in gas-transport systems was initiated by M.E.H. van Dongen (TU/e) and J. Gorter (Gasunie) in collaboration with Bram [3]. This work continued at TU/e until 2013, using the set-ups built by Bram [4–11].

Bram was born in a musical family and he was gifted with an absolute hear. In the early seventies Bram became member of the group *Au Joly Bois* and started building/modifying his own renaissance musical instruments, such as the viola, gamba, hurdy-gurdy, tromba marina, back-pipe, recorder flute, rauschpfeife and clarinet. For the restoration of recorder mouthpieces, he started a study of the optimal geometry of the flue-labium system. He combined acoustical measurements (spectral analysis) and flow visualization on an artificially blown organ-pipe/recorder like instrument in 1984. This study was inspired by the work of the instrument maker Philippe Bolton [12].

In 1985, A. Hirschberg replaced Poldervaart. Bram and Hirschberg decided to initiate a study on reed wind instruments. Thanks to contacts initiated by R. Caussé (IRCAM) the research was continued in close collaboration with French research groups (LAUM, IRCAM and LAM). The study on wind instruments was extended to human voiced sound production by Pelorson [13, 14]. Some aspects

FIGURE 1 – Musical aeroacoustic experiment by Bram Wijnands and Mico Hirschberg at TU/e around 1995.

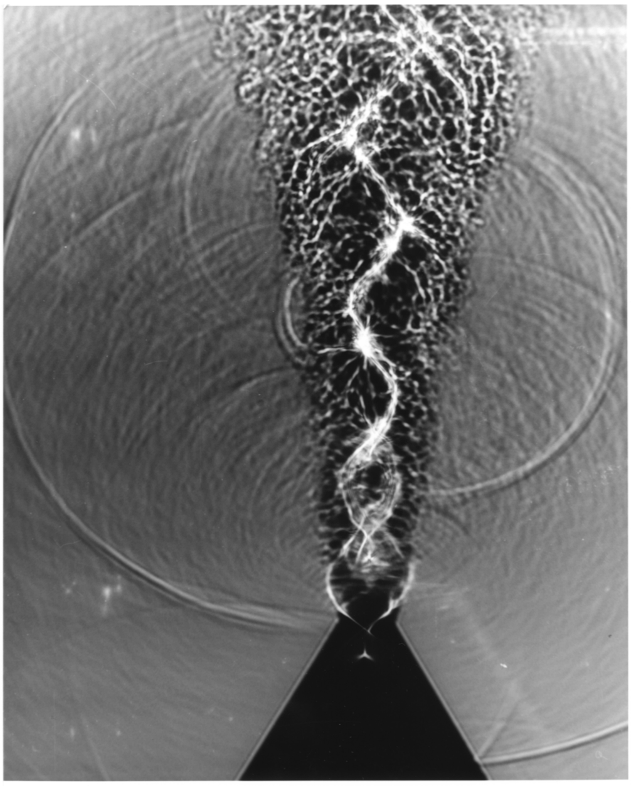

FIGURE 2 – Flow visualisation of jet screech. One observes the stationary shock waves due to steady expansion-compression oscillation of the jet. Cylindrical acoustic waves are emerging from the intersection of the shock with the shear layers. The waves on either sides of the jet are in opposite phase.

of the theory of Pelorson for the vocal folds oscillation were inspired by the study of human snoring by Aurégan and Depollier [15]. Pelorson continued this work at the Laboratoire pour la Communication Parlée (INP, Grenoble).

In 1995, Bram was offered retirement from the University, but he kept supporting actively the research for many years. Set-ups build by Bram are still being used in various laboratories or have inspired the building of similar set-ups.

The present paper provides a selection of the work of Bram and work inspired by Bram concerning the supersonic jet oscillations, the aero-acoustics of pipe flows and the human voiced sound production. A companion paper is dedicated to the work on musical wind instruments [16].

2 Aeroacoustic sources and propagation in internal flows

2.1 Self-sustained oscillations

Internal gas flows occur in a large number of technical systems including household appliances, ventilation systems in vehicles or buildings, cooling systems, IC-engine, power plants, gas transportation, gas turbine intake/exhaust systems, combustion chambers of rocket motors, etc. Frequently there is an associated generation of unsteady flow and pressure which inevitably leads to sound generation and possible noise problems. In extreme cases the pulsations can be a threat to the mechanical integrity of the system. In particular, the coupling between acoustic modes and unsteadiness due to flow separation at pipe discontinuities can result in strong pulsations.The basic mechanism of the

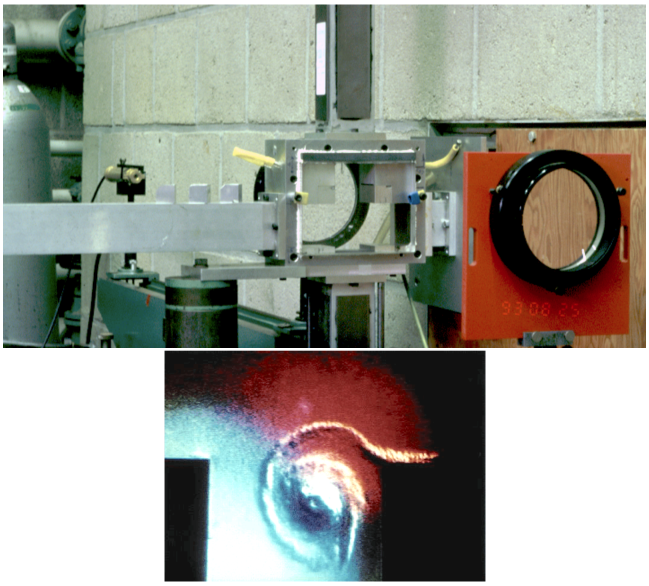

Figure 3 – Experimental setup for measuring the cross-junction geometry and a Schlieren visualization of a vortex with large sound amplitude (Bram and Olivier Schneider)

sound-production and coupling with the acoustic field where first studied at TU/e in the particular case of closed side branches by Bruggeman et al. [3]. In this T-junction, the shear layer, between the main flow and the stagnant gas in the side branch, is hydro-dynamically unstable. The acoustic standing waves, associated with resonant modes of the system, can synchronize the instability leading to periodic vortex shedding. Using pressure measurements and unsteady flow visualization using Schlieren effect, Bruggeman was able to predict the strength of the sound source up to moderate amplitudes of the acoustic field. He applied a simple model, in which the shear layer is represented by point vortices. Using the vortex sound theory developed by Powell [17] and Howe [18] he predicted the order of magnitude of the source strength. This study was extended to high amplitudes of the acoustic field by Kriesels et al. [19] using flow visualizations (see Fig. 3) combined with numerical simulations (vortex blob method).

More recently, the techniques developed by Bram have been applied at TU/e to the problem of whistling corrugated tubes by Nakiboglu et al. [20]. This study of corrugated pipes is currently extended at LAUM [21], on a test bench developed in collaboration with Bram.

2.2 Aeroacoustic propagation in ducts

In parallel with the visualization setup, a very precise acoustical measuring bench with cylindrical pipes was installed in Eindhoven. To obtain high precision measurements, special care had been taken with all parts of the measuring chain : Firstly, the very robust mechanical part had been machined with high precision (for example, the internal roughness of the tubes was less than 0.1 μm), secondly, the flow and the acoustic field in the tube were very accurately controlled and measured, finally, the acquisition and processing of the acoustic signals had been carefully designed specifically for this setup. All this made it possible to carry out benchmark measurements initially on closed side branches, at static pressure up to 16 bars [3] and later measurements of the reflection of an open pipe with flow by Peters et al. [4]. Incidentally, the wavenumbers of plane waves in turbulent pipe flows were measured and these are, with those of Ronneberger and Ahrens [22], the best measurements ever made of the acoustic damping with flow. They still serve as a reference for models [23]. A copy of this setup was installed at the LAUM by Ajello [24]. In this new version, loudspeakers were used rather than a siren allowing lock-in methods for signal analysis. This allowed to make complementary studies on the transfer matrix of basic elements in Eindhoven (at high level, high flow and high pressure) and in Le Mans (at moderate amplitudes and flow but at higher frequencies). At TU/e the double load method was used while the double source method was used at the LAUM. This was applied to sharp bends by Dequand et al. [25] and to diaphragms by Durrieu et al. [26] and Hofmans et al. [5, 6].

Thereafter, somewhere between the self-sustained oscillation studies and the measurement of discontinuities with flow, Testud et al. [27] has shown that the frequency range in which a thick diaphragm has the ability to whistle can be determined by measurements under anechoic conditions (see Fig.4). In this frequency range, the diaphragm acts as a gain amplifier. Those gain diaphragms have been used in association with a loss diaphragm by Aurégan and Pagneux [28] to demonstrate that a $\mathcal{PT}$-symmetric system can be realized in acoustics when the losses and the gain are exactly equal.

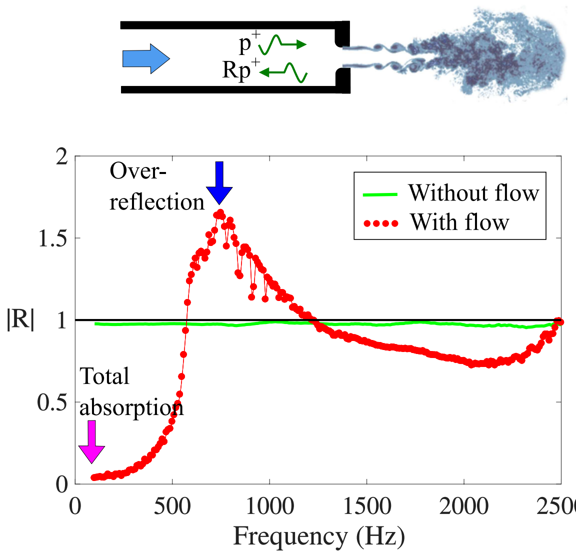

Figure 4 – Measurement in the LAUM setup of the reflection coefficient of a diaphragm with flow at the end of a tube. At low frequencies there is a total absorption as predicted by quasi-steady models [5]. At mid-frequencies, there is an amplification as predicted by [27]

During the European project Flodac (1997-2000), LAUM began to investigate the effects of flow on the performance of acoustic materials. The first measurements were carried out on the circular set-up developed in collaboration with Bram [29, 30] (see Fig. 5). Subsequently, a new rectangular bench was developed at the LAUM, keeping the same spirit, to be able to measure flat samples with a good precision. This allowed to highlight interesting phenomena such as instability above acoustic treatments with flow [31] and the questioning of Ingard-Myers condition [32].

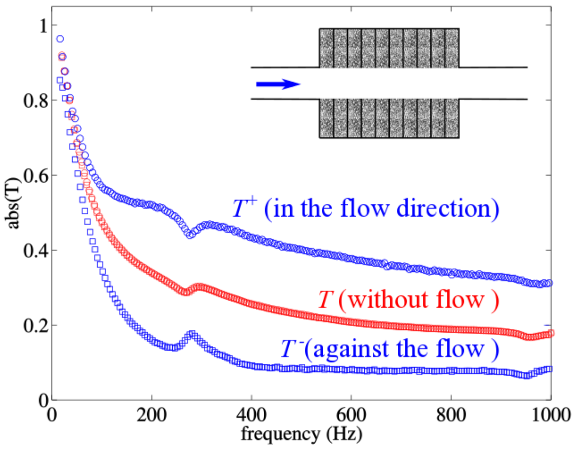

FIGURE 5 – Measurement in the LAUM setup of the transmission coefficient of partitioned chamber with porous material showing the effects of flow. [30]

3 Human voiced sound production

3.1 Flow separation in vocal folds

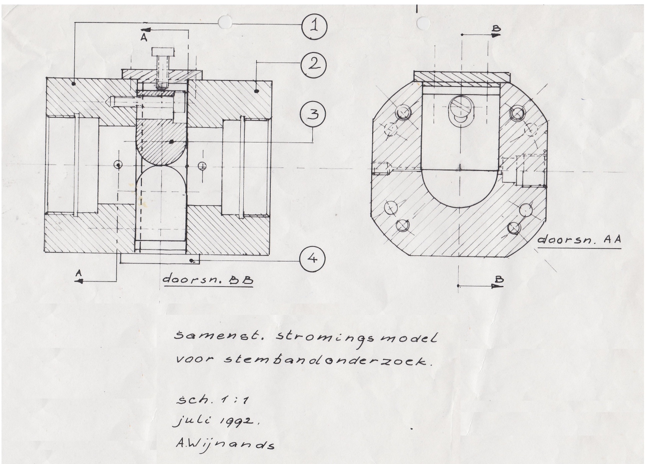

FIGURE 6 – Brams drawing of the first vocal folds replica built at TUe

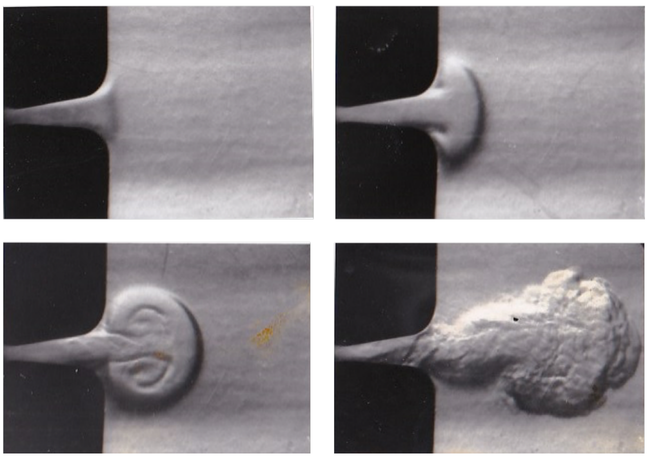

FIGURE 7 – Flow visualizations performed on another replica designed by Bram

The human vocal folds are elastic structures located inside the larynx. When adducted, i.e. put close together, the interaction with the airflow coming from the lungs can lead to a self-sustained oscillation of these structures. This constitutes the primary source of sound for voicing. In the 1990s, most physical descriptions of this phenomenon relied on the work of Ishizaka and Flanagan [33] which, implicitly, assumed a fixed flow separation point at the outlet of the glottis and a pressure recovery inside the vocal tract. Experiments by Scherer et al. [34] on mechanical replicas of the vocal folds however showed spectacular departures from the prediction of Ishizaka and Flanagan especially when considering a diverging glottis. The theoretical explanation for these departures lies in the fact that, at high Reynolds numbers, the flow through a diverging channel does not separate at the outlet of the glottis but further upstream, within the glottis. Since the volume flow velocity is determined by the position of the flow separation point, the pressure distribution along the glottis is also affected [13, 14]. In order to validate a theoretical model to predict the position of the flow separation point, Bram Wijnands at TU/e designed and built an experimental set-up based on a (3/1) upscaled mechanical replica of the vocal folds (see Fig. 6 and Fig 7).

3.2 Follow-up studies on human speech production

In collaboration with the Institut de la Communication Parlée, a direct improvement of the set-up of Bram was to include a siren upstream of the vocal folds replica in order to generate unsteady flow conditions [35]. Next, a step-motor was added in order to force one mechanical vocal fold into motion (designed by Herman Koolmees). This allowed one to introduce and to control unsteadiness in the experiments. Examples of results described by Deverge et al. [36]. Further research has been carried out in the vein of Bram Wijnands experiments. This included investigations on the influence of acoustical coupling on the vibration of the vocal folds [37], the influence of liquids (such as mucus) at the surface of the vocal folds [38]. Abnormal vocal folds configurations, related with some voice pathologies, such as the effect of a mechanical asymmetry of the vocal folds [39], of a growth at the surface of the vocal folds (such as a cyst) [40] have also been addressed by the team of Pelorson. Recently, a unique experimental set-up, shown in Fig. 8, allowed to mimic vowel-plosives sequences. It consists of a self-oscillating vocal folds replica, a deformable vocal tract and a motor-controlled lip replica [41]. This set-up can be seen as a mechanical voice synthesizer although its primary goal is to perform detailed and accurate measurements in order to test the relevance and the accuracy of theoretical models of voice production.

Flow visualizations benefit now of high-speed high-resolution imaging. An example of flow visualization performed on a rigid replica of the vocal folds is presented in Fig. 9. By comparison with Fig. 7, one can see the high quality of Bram Wijnands visualizations.

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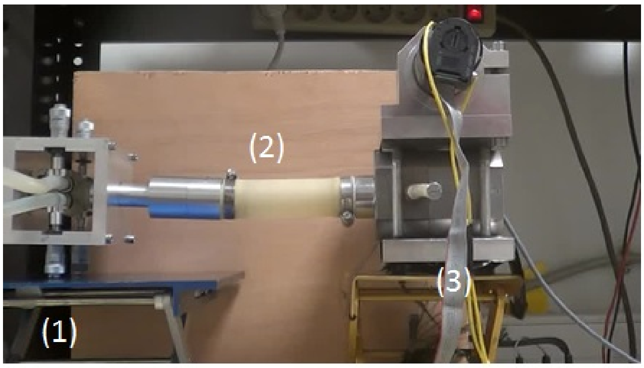

FIGURE 8 – Mechanical replica of a vowel-plosive sequence. (1) : self-oscillating vocal folds replica, (2) : vocal tract including a deformable portion, (3) motor driven lips replica.

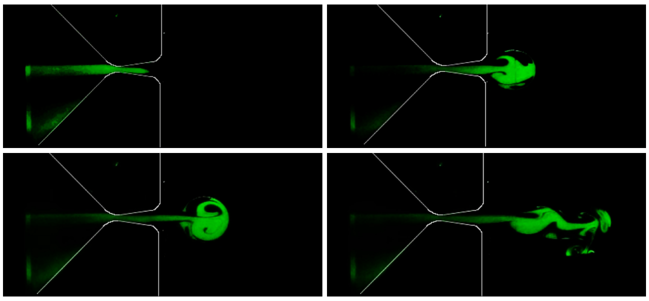

FIGURE 9 – Pictures from a high speed movie of the flow through a mechanical replica of the vocal folds (highlighted in white)

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