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Base Pressures and Energy Separation in Transonic Turbine Blading

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Abstract

This paper concerns unsteady near-wake flows on, and close to, the thick trailing edges of turbine blades, circular cylinders and similar bodies. Subsonic surface base pressures, and Eckert-Weise energy separation in the wake, are principal manifestations of the same phenomenon. Both are a direct result of von Kármán vortex shedding. The subsonic flow past a turbine blade having a thick trailing edge is still not well-predicted and this results from a lack of understanding of the flow past the trailing edge and into the wake. It is here argued that von Kármán vortex shedding is the principal cause of the subsonic base pressure deficit and the related energy separation in the wake. Parallels can be found in the behaviour of elastically-mounted circular cylinders and the caudal fin oscillation propelling fish. These should also affect supersonic flows although the physical causes are different. At supersonic speeds the trailing edge base pressure, and the energy separation in the downstream wake, exhibit different characteristics from the subsonic behavior and need to be treated differently. For supersonic flows, shock waves from a blade trailing edge may impinge on the adjacent suction surface adversely affecting the downstream boundary layer. Supersonic flows most often involve shock and expansion waves. Exotic vortex shedding also has an important role to play. In addition to experimental observation, the guidance of an analytical framework is needed. The eventual goal is accurate computational prediction for validation of computer models and prediction of flow behaviour.

Introduction

In 1943 Eckert and Weise [8] observed that the surface temperature over the rear portion of a circular cylinder in cross flow dropped by as much as 20°C compared with the upstream total temperature, resulting in a negative recovery factor. These findings were substantiated in the time-averaged experiments of Ryan [17] suggesting that vortex shedding from the bluff bodies might be responsible for the phenomenon. The measurements of Thomann [20] were the first to identify energy separation in the wake of a circular cylinder. Further work by Eckert and subsequently by Kurosaka *et al.* [12] and Ng *et al.* [16] provided further evidence for the Eckert-Weise effect. This is now referred to as 'energy separation' when dealing with the relationship between wake temperatures and vortex shedding. A further confirmation has been provided in highly resolved computational work by Hummel [11] who predicted temperature variations across a turbine blade wake that agree very closely with results presented in this paper. Similar total temperature redistributions were observed in both planar and annular cascades. The vortex shedding effects described in this paper are equally applicable to annular cascades and are likely to be present in rotating machines.

The non-uniform total temperature distribution observed in the cylinder wake also occurs downstream of turbine blades with thick trailing edges. This was investigated on a time-average basis by Carscallen and Oosthuizen [2] and on a time-resolved basis by Carscallen *et al.* [2] and Gostelow *et al.* [9, 10].

While good progress has been made experimentally and computationally, that is mainly confined to subsonic flows. This paper will indicate that further work is required for supersonic flows. This includes "exotic vortex shedding" which extends far beyond Eckert's original discovery for circular cylinders and subsequent consideration of turbine blade flows. There is certainly scope for more analytical and computational work. The experimental discoveries could serve to provide test cases for ongoing computational work and could shed light on the important physics of trailing edge and wake flows.

Subsonic Flows

Bodies with a blunt trailing edge are likely to shed vortices in a von Kármán vortex street. Trailing edges are often blunt for blade cooling and stressing reasons but may incur a high loss penalty. This loss penalty is greater than might be expected from a simple backwards-facing step and remained unexplained until high speed schlieren photography was used in cascades. The high losses were clearly associated with the shedding.

Energy Separation in Subsonic Turbine Blade Wakes

The objective of an early collaboration between Pratt and Whitney Canada and the National Research Council of Canada was to produce a gas generator for a PT6 engine with an aggressive turbine design. The single-stage, highly-loaded, high flow turning transonic turbine had a low wheel speed and was designed for a stage pressure ratio of 3.8 and stage loading of 2.5. This program was supported by a cold flow turbine rig that was three times engine size and matched the engine Mach and Reynolds numbers at design condition. Rig testing was carried out over a range of exit Mach numbers between 0.67 and 1.2.

During testing, the turbine stage gave some inexplicable results with a redistribution of the downstream total temperature field. In this ostensibly adiabatic arrangement the vane wakes exhibited a significant decrease in total temperature and their edges showed an unexpected increase. In order to resolve these anomalous results and obtain more detailed information over the Mach number range, the mid-span section of this high pressure turbine nozzle was tested in a large scale, low aspect ratio transonic planar cascade. The turbine nozzle profile had a 6.35mm diameter trailing edge. Schlieren imaging at high subsonic speeds showed intense von Kármán vortex shedding from this nozzle (Fig. 1). It was clear that the wake energy redistribution was associated with the vortex shedding.

Downstream wakes, at the mid-span of the cascade middle vane, were traversed with fast response temperature and pressure probes to quantify any entropy increase. 'Hot spots' of increased total temperature were discovered at the edge of the wake and 'cold spots' of decreased total temperature were located close to the wake centreline. The non-uniform downstream total temperature and total pressure distributions were a source of entropy production, and hence of additional loss.

At high subsonic speeds, the thermo-acoustic effect of energy separation was present. At the outer edges of the wake the stagnation temperature was 5^{o}C higher than that of the incoming fluid whilst on the wake centreline the stagnation temperature was12°C lower than the incoming fluid. This time-averaged temperature separation was a manifestation of the Eckert-Weise effect [8].

Investigation of this phenomenon involved measuring time-resolved temperature variations within the fluctuating wake and relating these to the previously observed time-average total temperature variations. Hitherto attempts to obtain such time-resolved measurements had been limited by the inadequate bandwidth of the available temperature instrumentation.

Using innovative wide bandwidth temperature probes from Oxford University [1] the anticipated fluctuations were detected. The frequency of vortex shedding temperature from the blades was of the order of 10 kHz and it was considered necessary to make total temperature measurements with a bandwidth approaching 100 kHz for the energy separation phenomenon to be resolved and identified. Phase-averaged contours of total temperature and pressure were constructed from simultaneous fast-response measurements of the quartz rod mounted thin film gauge, and a Kulite pressure transducer respectively.

From these measurements, contours of time-resolved entropy increase at the measurement location, downstream of the trailing edge, were calculated from the Gibbs' entropy relation:

$$s_2 - s_1 = C_p \ln\left(T_{02}/T_{01}\right) - R\ln\left(p_{02}/p_{01}\right) \qquad (1)$$

States 1 and 2 are taken to be the inlet and downstream measuring planes respectively. As an example the total temperature contours are shown in Fig. 2 and the entropy contours in Fig. 3, for *Ma* = 0.95. Positive *y* values refer to the suction surface and negative *y* values the pressure surface. The relatively cool vortical structures on the wake centreline are seen, as are the hot spots on the edge of the vortex wake. The entropy plot of Fig. 3 shows that the entropy generation is more or less concentrated in the wake centre region resulting from the coalescence of the suction surface and pressure surface boundary layers. However, the hot spots of Fig. 2 are essentially outside of this entropy-laden wake. The separation of the total temperature and pressure is essentially an inviscid process, governed by equation (1). The cold spots between the hot spots are expected from the conservation of total energy, resulting in the unavoidable overlapping of the cold spots with the wake core.

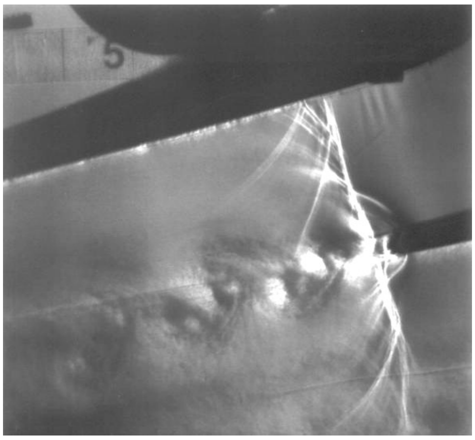

Figure 1: von Kármán vortex shedding at *Ma* = 0.97

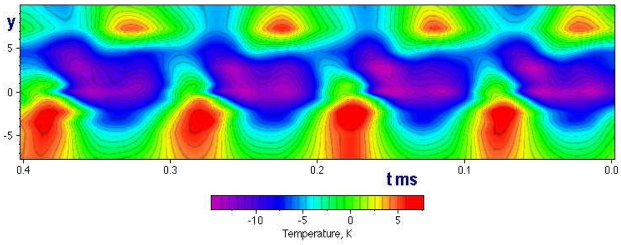

Figure 2: Time-resolved temperature contours downstream of the cascade trailing edge.

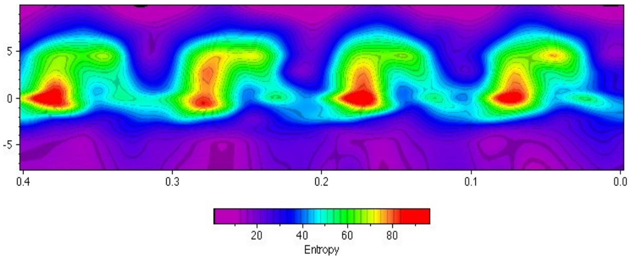

Figure 3: Time-resolved entropy contours downstream of the cascade trailing edge.

An indication was that the time-averaged measurements were in agreement with previous thermocouple measurements showed very good agreement. The vortex shedding fluctuations were in excellent agreement with the steady state measurements.

Base Pressures on Subsonic Blades

The base pressure is strongly dependent on Mach number. At subsonic speeds, shocks only begin to play a role as the velocit*y* reaches critical levels. In general, the unsteady process of vortex shedding is more important. At supersonic speeds, the main causes of low base pressure are the strong spatial progression of pressure through shocks and expansions. There are therefore two distinct compressibility regimes.

At subsonic speeds vortex shedding is the principal cause of a base pressure deficit. Turbine blades with thick trailing edges have an area of reduced static pressure creating a considerably increased base drag, reducing the blade's efficiency. Cicatelli and Sieverding conducted an investigation into the effect vortex shedding had on the base region flow [5]. They found that the pressure in this region fluctuated by as much as 8% of the downstream dynamic head near separation and by 4.8% in the base region. Fluctuations in base region pressure indicate that the instantaneous base pressure could differ from the time-averaged value; this inadequate representation resulted in poor computational results if steady state methods were used. Time-resolved pressure distributions give information on fluctuations and corresponding drag coefficients. Computations for design using steady state methods will be erroneous for much of the vortex shedding cycle. MacMartin and Norbury concluded that, for bluff body flows, "calculation methods which neglect base pressure effects are incapable of accurately calculating the flow patterns or the total pressure loss" [13]. At subsonic speeds the unsteady vortex-shedding process is the most important cause of base drag; a relationship that was investigated in the measurements. For subsonic speeds, low pressures at the trailing edge are an essential facet of the vortex shedding process resulting in increased drag for bluff bodies and turbine blades. Base pressures were measured at the extreme trailing edge of the turbine blades. The results were supplemented by earlier results obtained by Carscallen and Oosthuizen [2] who presented contour plots of time-averaged total temperature differences between the inlet and outlet gas streams and total pressure loss coefficients for three isentropic exit Mach numbers. The similarity between the contour plots of time-averaged total temperature difference and loss coefficient was striking, indicating a strong correlation between the two phenomena.

Supersonic Flows

As the discharge Mach number becomes supersonic the trailing edge shocks become oblique and the origin of the vortex street migrates from the trailing edge to the confluence of the two trailing edge shear layers [16]. Only free-steam disturbances are effective in provoking the vortex shedding instability [7]. The lateral distance between the incipient vortices at the downstream location is shortened. Observed Strouhal numbers need to be based on these shorter distances for supersonic flow. Based on the CFD results, the vortex shedding frequency was calculated to increase from 7.91 kHz at Ma=0.7 to 13.91 kHz at an exit Mach number of 1.16. The effective length of the shear layers was clearly reduced and the shedding frequency was increased. Nevertheless for much of the time the vortex shedding continued.

Exotic Modes and Energy Separation in Blade Wakes

At supersonic speeds the base pressure deficit at the trailing edge and 'exotic' energy separation in the downstream wake exhibit different characteristics and need to be treated differently. Parallels can be found in the behaviour of elastically-mounted circular cylinders and the caudal fin oscillation propelling fish. For supersonic flows shock waves from a blade trailing edge may impinge on the adjacent suction surface adversely affecting the downstream boundary layer. The physics of supersonic flows specifically involves shocks and expansions; these flows, and exotic vortex shedding, need particular awareness and treatment. von Kármán vortex shedding may still be present at supersonic speeds but its inception, shape and frequency will differ from the more usual configurations encountered at subsonic speeds.

Similarities between the vortex shedding structures occurring in low speed oscillating cylinder and aerofoil flows and transonic cascade flows suggest that the existence of an oscillating body is not a fundamental requirement. The wake instability can be caused by an oscillating flow mechanism and it is argued that the pressure field associated with the trailing edge shocks exerts the fluctuating lateral force which is essential for the vortex shedding process at transonic and supersonic speeds.

Findings, from schlieren visualization, computational work and a separate hydraulic analogy experiment, have shown the shock - wake interaction structure at the confluence of shear layers to be particularly dynamic. As a result an oscillatory flow is set up causing the observed changes in vortex shedding. It is therefore interesting that the vortex wake shed by an oscillating cylinder reveals a similar behaviour. Williamson and Roshko [21] identified several vortex-shedding modes as a function of wavelength and amplitude of oscillation (Fig. 6).

It is also clear that the classifications provided by Williamson and Roshko [21], and by Ponta and Aref [17], have the potential to be useful not only for the field of vortex-induced vibration but also to classify problems involving both stationary and oscillating aerofoils and turbine blades at transonic speed.

The von Kármán vortex street of Fig. 1 is represented by 2S. In the context of the transonic turbine blading the "couples" observed in the Fig. 4 cascade tests are described by 2P. In the P+S mode of Fig. 5 a pair and a single vortex are shed each cycle; the "doublets" would seem to reflect this P+S behaviour.

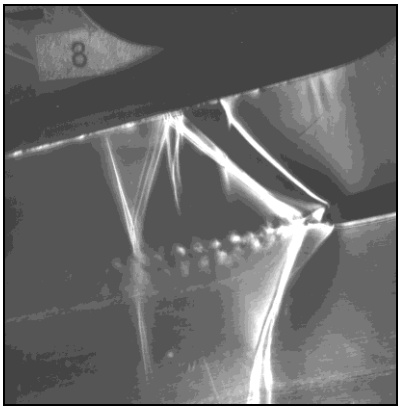

Figure 4. Shedding of Couples at *Ma* = 1.07

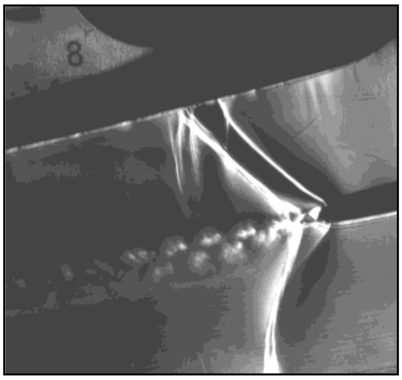

Figure 5. Shedding of Doublets at *Ma* = 1.07

Base Pressures on Turbine Blades

A detrimental flow phenomenon affected by vortex shedding is low base pressure. Blades with thick trailing edges have an area of static pressure deficit around the trailing edge. This creates a considerable increase in base drag at subsonic speeds and reduces the blade row's efficiency.

Sieverding *et al.* [19] conducted an investigation into the effect vortex shedding had on the base region flow. It was found that the pressure in this region fluctuated by as much as 8% of the downstream dynamic head near separation and by 4.8% in the base region. The instantaneous base pressure could be significantly different from the time-averaged value.

The base pressure is strongly dependent on Mach number. For subsonic speeds low base pressure is an essential facet of the vortex shedding process resulting in increased drag for bluff bodies and efficiency losses in turbine blades. At subsonic speeds, shocks only begin to play a role as the velocity reaches critical levels and, in general, the unsteady process of vortex shedding is more important. At supersonic speeds, the main causes of low base pressure are the strong spatial variations of pressure through shocks and expansions. These are therefore two distinct compressibility effects.

Denton and Xu [6] and Mee *et al.* [14] showed that a significant proportion of the total loss at high speeds could be attributed to the base pressure. Carscallen *et al.* [2] found that a strong base pressure deficit was accompanied by the strongest amplitude of vortex shedding. Motallebi and Norbury [15] measured the base pressure and shedding frequency over a range of Mach numbers and found that a large drop in base pressure was accompanied by an increase in shedding frequency. The most comprehensive base pressure correlation is that of Sieverding *et al.* [19].

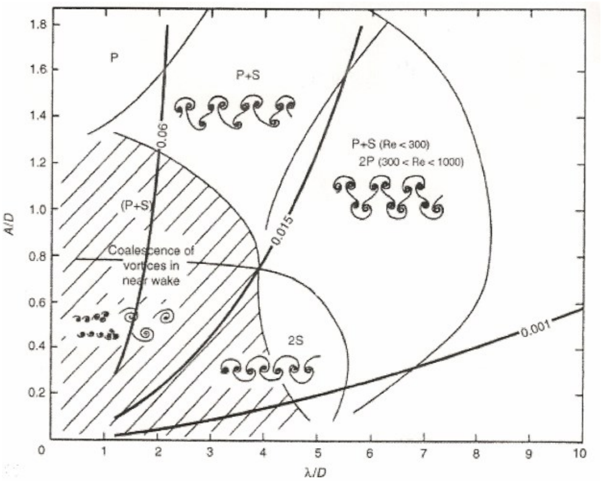

Figure 6. Map of vortex synchronization regions in the wavelength-amplitude plane [17, 21].

Conclusions

Experimental and analytical work on a high speed planar cascade was examined to obtain a clarification of the various processes. The turbine blades had a blunt trailing edge; hot spots were detected at the edges of the wake and cold regions were located close to the wake centreline. Vortex shedding frequency increased with Mach number. The highest base pressure losses coincided with the strongest wake energy separation. The analysis indicated that, at subsonic speeds, energy separation and base pressure deficit were caused by vortex shedding. Coincidence was observed between the most active vortex-shedding behaviour and the strongest energy separation and base drag. Energy separation and base pressure, and their strong interactions, have been observed in subsonic bluff body flows whenever suitable techniques were deployed. At supersonic speeds exotic vortex shedding modes were in good agreement with computational predictions. Awareness of vortex shedding in all flow regimes is essential to minimize the adverse impact of energy separation and base drag.

Acknowledgments

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Nomenclature

A : amplitude parameter
C_p : specific heat at constant pressure
Ma : isentropic exit Mach number
p : pressure
Re : Reynolds number
s : entropy
t : time
T : temperature
y : transverse distance
λ : wavelength parameter
Subscripts:
s : static
0 : stagnation value
1 : upstream value (at inlet)
2 : downstream value (in measuring plane)

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