Wake vortex mechanisms behind semi-porous cylinders

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There has been much recent interest in the combined structural and aerodynamic properties of porous metal foams, but there does not yet appear to be a consensus on the aerodynamic behaviour of these foam materials. A comprehensive analytical and experimental study with special attention to scaling was carried out in order to examine the flow around cylinders coated with porous metal foam and characterize the effects upon the mechanisms governing shear layer separation, vortex shedding and wake formation. Results have yielded a correlation between the distance separating the detaching shear layers and the vorticity losses in the near-wake. It seems that it is the coating configuration, rather than geometry, that influences vortex shedding, and therefore foams affect the flow in a similar way as shrouds or bleeding systems.

I. Nomenclature

d	=	cylinder diameter
U_∞	=	undisturbed flow speed
Γ	=	vortex strength
Γ_0	=	theoretical vortex strength
St	=	Strouhal number
f	=	vortex shedding frequency
k	=	base pressure parameter calculated as $\sqrt{1 - C_{ps}}$

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k'	=	base pressure parameter calculated as u_s/U_∞
ϵ	=	vorticity ratio
d'	=	distance between detaching shear layers
C_{p_s}	=	base pressure coefficient
ν	=	kinematic viscosity
C_p	=	surface pressure coefficient
p_s	=	base pressure
p_0	=	reference pressure
ρ	=	density
θ	=	angle from stagnation
x	=	distance from cylinder leeward side
u_s	=	vortex speed relative to flow

II. Introduction

VORTEX shedding behind bluff bodies remains a subject of some interest, owing to its fundamental importance in predicting and modelling unsteady aerodynamic loads and noise.^{1,2} Despite much work on the subject, some of the underlying mechanisms of the shedding process remain unclear, especially within the near wake; the processes are even further complicated if the bluff body is permeable. Because vortex shedding involves complex, nonlinear interactions between different structures at different scales, a closed-form solution becomes almost intractable.

Typically, the focus of bluff-body flows has been on drag control; one common approach is to obtain the time-mean drag as a function of Reynolds number $Re = U_\infty d/\nu$ (where U_∞ is the free-stream velocity, d is the characteristic length-scale and ν is the kinematic viscosity), and examine how the control inputs affect the results. Another approach has been to obtain velocity spectra and identify the effect of the control input upon the vortex shedding Strouhal number $St = fd/U_\infty$ (where f is the frequency). Given that the drag is coupled to the vortex strength by means of the momentum equation, it is curious that there has been much less work on the characteristics of the vortex wake itself. Furthermore, work on bluff-body flows and vortex shedding appears to be focused on either the near wake mechanics^{3,4} or the boundary layer and aerodynamic loading,^{5,6} with the only coupling being via the base pressure at the rear stagnation point.⁷

Recently, metallic foams have been suggested as a surface treatment for passive flow control, as they also offer advantageous structural and acoustic characteristics. There have been claims that given the particular geometry and topology of these materials, metallic foam coatings are able to provide significant reductions in the aerodynamic loading caused

by bluff-body vortex shedding by interfering with the vortex formation process.^{8,9} This, however, remains a subject of some debate: the effect of these foams upon the mechanisms of vortex shedding and wake formation has yet to be fully explained, and the appropriate scaling of the flows remains unclear.

For the case of these metallic foam coatings, conventional scaling parameters like Re and St will necessarily be insufficient to describe the phenomena. At the very least, it would be expected that some parameter including the wall shear velocity or some equivalent ‘roughness length-scale’ of the foam will be required. Without this, the direct comparison of the flow characteristics around foam-covered bodies may not be meaningful. Also, if the effect of the foam can be reduced to a wall-shear parameter, the specific topology of the foam would become irrelevant. The problem is further compounded if the body is nonuniformly coated in foam: significant drag reduction has been recorded for the case of a cylinder partially covered in foam, but it is not clear whether the scaling of these results is appropriate.¹⁰

A parametric analysis and state-space approach is therefore required in order to identify the scaling characteristics of bluff bodies with foam (or indeed any roughness) coatings. This technique is not novel,¹¹ but has yet to be extended to all of the variables known to be associated with vortex shedding.

III. Modelling periodic wake flows

Because vortex formation and shedding is a dominating characteristic in bluff-body flows, any parametric analysis will necessarily be required to capture the effects of this phenomenon. Since wake vortices are formed by the roll-up of the separating shear layer, the rate of vorticity transport from the shear layer should be linked to the growth rate of the vortex being formed prior to shedding. For a bluff body of characteristic lengthscale d the wake vortex circulation Γ , St and the base pressure parameter $k = \sqrt{1 - C_{ps}}$ can be related as

$$\frac{\Gamma}{U_{\infty}d} = \frac{1}{2St}\epsilon k^2, \quad (1)$$

where $\epsilon = \Gamma/\Gamma_0$ is a ‘transport effectiveness factor’; this must be included as not all of the shear layer vorticity is rolled into the wake vortices.^{7,12} This ratio ϵ is not universal, and is expected to vary with both geometry and surface conditions. However, its variation with Re for certain initial and boundary conditions has been mapped.¹³ Equation (1) therefore provides a relevant set of velocity, length and time scales for the phenomenon.

However, two additional length scales are known to be associated with bluff body flows: the distance between the detaching shear layers d' and the formation length l_f (defined as the distance required for the wake vortices to become fully-formed). For canonical bodies such as

smooth cylinders, these length-scales vary monotonically with d and Re , and are therefore not independent; however, with the introduction of geometric irregularities,¹⁴ surface roughness (or even free-stream turbulence⁴) these parameters can be caused to vary independently.

Because C_D must vary with Γ to satisfy the momentum equation over the wake width, a relationship between d' and C_D (and, indirectly, Γ) is available from the momentum balance as

$$C_D = -C_{ps} \frac{d'}{d} \quad (2)$$

where C_D is the coefficient of drag and $C_{ps} = (p_s - p_0) / (1/2\rho U_\infty^2)$ is the base pressure coefficient.¹⁵

It is known, however, that the base pressure is very sensitive to the vortex shedding regime in presence¹ as well as to any surface permeability, and therefore must be included as an independent parameter if the behaviour of bluff bodies fitted with porous coatings is to be described.

The integrated flow characteristics (such as k , for example) of a bluff body in cross flow may then be expressed as

$$k = F(St, l_f, d', \Gamma, \epsilon) \quad (3)$$

where F is some function yet to be described.

An exploration of this state-space is therefore required in order to develop a model capable of describing the behaviour of any bluff body for which these parameters remain independent.

IV. Experimental methodology

Experiments were conducted using cylinder models of aspect ratio $d/L = 7.5$ (where L is the cylinder length). All models had similar maximum (outside) diameters, but with different sectors of the circumference coated to a depth of $0.1d$ with metallic foam with porosity of 97% and permeability of $1.72 \times 10^{-7} m^2$. The spanwise flow was constrained by end-plates measuring at least $5d$ (Figure 1). The models were installed in a recirculating wind tunnel facility (with a free-stream turbulence intensity of less than 0.5%), and measurements were collected at $3.5 \times 10^4 \leq Re \leq 1.05 \times 10^5$. Measurements were carried out using a four-beam laser-Doppler anemometry (LDA) system having a measurement volume of approximately $100 \mu m$ in diameter $\times$ $500 \mu m$ long, positioned outside of the wind tunnel facility. Instantaneous cross-flow fields were also obtained using a particle-image velocimetry (PIV) system, yielding a spatial resolution of $\sim 0.06d \times 0.06d$ per pixel. Surface pressures were obtained using 20 pressure taps positioned symmetrically about a half circumference, simultaneously sampled using differential pressure transducers having a full-scale range of ± 250 Pa. Phase reference information was collected using a single hot-wire probe positioned

on the edge of the vortex wake. The mean uncertainty for all velocity measurements was estimated to be $\sim 1\%$.

Figure 1. Schematic representation of the model, with coordinate system (not to scale).

Four configurations of porous coatings were considered (see figure 2): one with the leading-edge area covered, another with the trailing-edge area covered, one which was completely covered, and a last which was completely covered except for a 90° sector about the leading edge. A smooth cylinder was also tested for comparison. These model geometries were selected specifically to explore independently the effects of the foam coating on the boundary layer development, shear layer separation and vortex formation regions (it has already been observed that the effect of porous coatings is significantly different in cases where it is applied only to the leading or trailing edges of the cylinder¹⁰).

Figure 2. Configurations of porous coatings - white indicates solid surface, grey indicates foam coating. (a), leading-edge coating; (b), trailing-edge coating; (c) 270° sector, and (d) completely coated.

The pressure drag on the model was estimated by integrating the surface pressures obtained from the pressure taps. Although the bandwidth of the pressure sampling system was limited to ~ 100 Hz, the signal attenuation was sufficiently low at the vortex shedding frequency to obtain estimates of the vortex-induced periodic loading.

V. Analysis of Results

A. Vortex shedding frequency

The vortex shedding frequency of each configuration is presented in Figure 3. All coating configurations increased the shedding frequency, with the exception of the leading-edge coating which decreased it significantly.

Figure 3. Strouhal number variation for $Re = 3.73 \times 10^4$ to $Re = 1.12 \times 10^5$ for different coatings

Higher vortex shedding frequencies are typically associated with a decrease in l_f ;⁴ it may therefore be inferred that porous coatings shorten the formation length (again, with the exception of the leading-edge coating). Also, the invariance of St with Re through the subcritical regime is generally attributed to a balance between the the base pressure and the thickness of the separating turbulent shear layers. Since the coatings increase shedding frequencies, this suggests that the coatings are having a more significant effect upon the base pressure than the shear layer thickness.

The leading-edge coating case may be pathological, since the shear layers are expected to detach at or near the azimuthal foam-wall interface (90° from the forward stagnation point). This is likely to delay vortex formation, increasing formation length.

B. Lift and drag spectra

The spectra of lift and drag were obtained from the integrated surface pressure. Results show a clear peak in amplitude at the vortex shedding frequency (Figure 4).

For the drag spectra two maxima can be observed: one at the vortex shedding frequency and the other at twice this value, consistent with previous findings.^{16–18} It would seem sensible to expect the maximum power in the drag spectrum to occur at twice the vortex

Figure 4. Power spectral distributions of drag and lift over different coatings at $Re = 1.12 \times 10^5$.

shedding frequency, since drag is effectively a rectified phenomenon.¹⁷ In this case, some asymmetry has been introduced either in the coating or from ground effect.

The broadness of the peaks observed in the load spectrum in the case of the solid cylinder agrees with previous work, in which the shedding frequency has been shown to vary by as much as 15% in the subcritical regime (TrSL3).^{13,19} The spectra for the coated cases do not demonstrate this effect, suggesting a stabilizing influence also consistent with previous work.^{20–22}

C. Pressure distributions

The surface pressure distributions for all configurations at $Re = 1.3 \times 10^5$ are shown in Figure 5. The pressure distribution of the solid cylinder is also compared to published data for validation purposes (Figure 6).

Results show different separation points (identified as the starting point of the base pressure plateau) as the different coatings interact with the flow in different ways.

The data suggests that every surface pressure distribution can be recovered provided those of the solid and fully coated cylinders are known: Figure 5 shows the pressure distributions around the cylinders with different coating configurations. For the partial coating cases, the distributions can be well-approximated by azimuthally blending the uncoated and fully-coated case results. This approximation is less accurate for the 270° coating owing to the more complex mechanics at the foam-wall interface. Results show higher pressures on the leading side of the cylinder when the coating is applied, which can be attributed to a slowing of the flow inside the porous coating.

On the trailing side of the cylinder the pressure is higher when the porous coating is applied, consistent with the presence of an entrainment layer inside the porous coating. The

Figure 5. C_p distribution for all coatings at $Re = 1.12 \times 10^5$

Figure 6. C_p distribution for reference case ($Re = 1.06 \times 10^5$, $L/D = 7.17$). **Szepessy and Bearman**,¹⁸ $Re = 1.3 \times 10^5$, $L/D = 10$; **Achenbach**,⁵ $Re = 10^5$, $L/D = 6.66$; and **Klausmann & Ruck**,²³ $Re = 6.4 \times 10^4$, $L/D = 10.7$.

presence of this entrainment layer has been associated with the foam coating's effect on base pressure,^{23–25} owing to the effect of the entrainment upon the velocity fields. This is also consistent with experimental observation (Figure 7).

Given that both the solid cylinder and the leading-edge coating configuration exhibit the same base pressure coefficient, and that the base pressure is a strong predictor of the shedding frequency, it is surprising that the spectra in these cases do not agree. Because the

Figure 7. k as a function of Re for different configurations.

foam coatings are expected to affect the formation and shedding of the shear layers, it is reasonable to expect that they would affect the balance between base pressure and shear layer thickness and therefore change the shedding frequency. A similar effect has been observed for shear layers artificially thickened by free-stream turbulence.⁴

D. Drag

Total drag measurements up to $Re = 1.3 \times 10^5$ show that both the full coating and the leading-edge coating increased the drag experienced by the cylinder, while the trailing-edge and 270° coatings decreased it (Figure 8) by as much as 17%.

The application of foam coatings in various configurations has some interesting effects upon the drag characteristics. The full coating increases the drag coefficient relative to the solid cylinder, suggesting that the increased viscous and pressure losses within the foam dominate over any advantageous effect on the wake characteristics.

On the other hand, the 270° coating decreased the total drag over the cylinder to a value similar to that of the trailing edge coating. This is significant, as the only difference between these two cases is the momentum loss between 45° and 90°. No major change in the flow mechanics around the foam-wall interface is apparent.

The total drag D over the cylinder can be described as the sum of the pressure drag D_p and the “foam drag” D_f , such that $D = D_p + D_f$. An estimate of the values of these components for the various cases tested is presented in Figure 8. As expected, the pressure drag is lower for both the trailing-edge and 270° coating cases and higher for the case of the leading-edge coating; this, again, is the result of the trade-off between increased losses

Figure 8. Total (continuous lines) and pressure (dashed lines) drag coefficients.

in the foam around the leading-edge region and the decrease in base pressure caused by flow entrainment around the separation points. In light of these results, the difference in D_f between the trailing-edge coating and the 270° coating case is somewhat puzzling: if increased drag is caused by a dominance of the wall-shear in the leading-edge region, it follows that since the fully-coated cylinder exhibits more drag than the 270° case, this increase in drag should be the result of increased D_f . However, this does not appear to be the case: it is D_p which dominates.

When applied uniformly over the entire surface, the foam appears to behave like conventional roughness, increasing wall shear but decreasing the base pressure.²⁶ For the 270° coating case, then, it is the pressure step at the foam/wall interface, rather than some specific property of the metallic foam topology, which makes this configuration so effective at decreasing the drag over the cylinder. Note that the estimated pressure drag for the leading-edge coating is greater than the total drag: this is an artifact of the spatial resolution of the measurements.

E. Vortex strength

The phase-averaged wake vortex circulation was obtained at $x/D = 3$, where the vortices were sufficiently well-developed that the roll-up was complete,⁷ and results are shown in Figure 9a.

Current models of vortex shedding provide a well-documented relationship between the base pressure and vortex strength (Equation 1).¹⁴ However, taken together with Figure Figure 7, these results demonstrate that the foam coatings has caused this relationship to

Figure 9. (a) Vortex strengths and (b) vorticity ratios for different coatings.

break down. There appears to be no clear trend in the results.

Vorticity ratio data (Figure 9b) shows the vortex shedding process to be more efficient for the fully coated cylinder, with $\epsilon \approx 50\%$ for all Re ; this result is in agreement with previous work.^{12,27} Since the configurations shedding the strongest vortices are not necessarily the ones with the highest ϵ demonstrates that the mechanics of vortex shedding is indeed affected by the presence of the coating.

Despite producing the strongest vortices, the leading-edge coating case has the lowest ϵ , consistent with a high level of vorticity losses to the surrounding flow.⁴ The vorticity ratio was lowest for the case of the solid cylinder, although this may be exaggerated by the scaling.

F. Formation length

The formation length was defined using the method of Bloor & Gerrard,⁷ and results are presented in Figure 10.

Considering what is known of the relationship between St , k and l_f , these results are unexpected. The 270° partial coating exhibited one of the highest vortex shedding frequencies; its formation length would therefore be expected to be small. However, the data suggest that this case developed the largest l_f . These results also suggest that the leading- and trailing-edge coating cases have similar formation lengths. This, too, is unexpected.

G. Shear layer separation length-scale

The distance between shear layers at detachment was obtained in two different ways: first by using (Equation 2) with the base pressure coefficient measured experimentally under the

Figure 10. Normalized formation lengths.

coating, and then by using the vortex relative velocity to extract the base pressure parameter

$$k' = \frac{U_\infty + u_s}{U_\infty} \quad (4)$$

where u_s the speed of the vortices relative to the flow. Because both formulations can be derived from the momentum balance it would be expected that, at least for the baseline case of a solid cylinder, k and k' should have the same value.

Figure 11. Normalized detachment distances using (a) $k' = u_s/U_\infty$ and (b) $k = \sqrt{1 - C_{ps}}$.

The results are shown in Figure 11, and demonstrate that using the pressure underneath the foam as an approximation of base pressure in order to estimate d' can introduce discrepancies in the results. This assumption of equivalence between base pressure and ‘core’ pressure, often required to accommodate mechanical model design constraints,²³ appears to

fail. This is an important observation for the case of trailing-edge coatings, which have recently earned more attention.²³ The increase in the distance between shear layers was also observed in direct flow velocity field measurements (Figure 12), indicating that these results are unlikely to be result of some artifact of the measurement technique.

Figure 12. Wake visualization using PIV at $Re = 1.12 \times 10^5$.

VI. State-Space model

Isosurfaces of k at $Re = 9.75 \times 10^4$ for all configurations are presented in Figure 13. These results suggest that there is indeed a change in vortex shedding regimes when the different coatings are applied, since the different cases occupy discrete volumes in the state-space. The fact that some of these do overlap indicates some degree of universality.

When plotted as a function of formation length (Figure 13a), the leading-edge coating occupies a space at low St and high l_f , demonstrating that its behaviour approaches that of a blunt obstacle. The baseline solid cylinder occupies a space at $St \sim 0.18$, large k and small l_f . The various partial-coating cases occupy spaces at different (but larger) l_f . Given a particular location occupied by a coated-cylinder model within this 6-dimensional state-space, then, it should be possible to infer the surface condition. Furthermore, all six variables are needed to completely define the state, so that no unique, universal relationship between l_f and St may exist (see Bloor & Gerrard⁴).

Plotting as a function of d' (Figure 13b), the leading-edge coating results in $l_f/d \sim 1$, consistent with the behaviour of blunt bodies. The remaining cases result in increased d' : a result that was also supported by velocity field measurements. Interestingly, the projections of isosurfaces of k in $d'-St$ space and $\epsilon-St$ space (Figure 13d) are nearly identical, strongly suggesting a correlation between the vorticity ratio and the spacing of the detached shear layers. Because ϵ is arguably the most elusive parameter in the study of vortex shedding (it cannot be directly measured and is always highly uncertain), this indication that d' (which is directly measurable) may be used as a proxy is significant.

Plotting as a function of Γ (Figure 13c), the baseline cylinder and the partial coatings are concentrated together, with the leading-edge coating being the only outlier. Although the leading-edge coating case has already been identified as being somewhat pathological, these results suggest that the porous coatings affect not only the shear layer detachment but also the vortex roll-up process.

Figure 13. Vortex shedding state-space model at $Re = 9.75 \times 10^4$.

VII. Conclusions

An extensive, multi-parametric experimental measurement campaign was carried out to characterize the behaviour of cylinders with different configurations of porous coatings. The results have demonstrated that there are indeed quantifiable differences in the vortex wake behind smooth cylinders and those covered with porous foam, consistent with the understood effects of surface porosity on the base pressure and shear layer thickness.

Instantaneous reconstructions of the phase-averaged vortex wakes have enabled the distribution of vorticity within the wake to be inferred, and work is currently underway to relate direct force measurements to the integrated circulation of the shed vortices. Although this approach is not novel (see Bloor & Gerrard⁷), a refined methodology is under development which, together with the full state-space approach, may address some of the inconsistencies identified.

If porous coatings are applied in the trailing-edge region, the generated entrainment layers must necessarily affect the recirculating wake flow, which should lead to a decrease in the formation region length. Moreover, since the shear detachment is delayed, the shear layer separation distance will decrease, resulting in increased vortex shedding frequency independent of Re . The application of porous coatings, especially highly permeable ones such as metallic foams, causes the existing models for vortex formation and shedding to fail; a full state-space approach is therefore necessary in order to characterize the flows around these geometries.

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