MODELING AND EXPERIMENTING

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Abstract:

Experimental activity is traditionally identified with testing the empirical implications or numerical simulations of models against data. In critical reaction to the 'tribunal view' on experiments, this essay will show the constructive contribution of experimental activity to the processes of modeling and simulating. Based on the analysis of a case in fluid mechanics, it will focus specifically on two aspects. The first is the controversial specification of the conditions in which the data are to be obtained. The second is conceptual clarification, with a redefinition of concepts central to the understanding of the phenomenon and the conditions of its occurrence.

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In the tribunal function traditionally assigned to experimental activity, experiments are viewed as the place where empirical implications or numerical simulations of theoretical models are confronted with outcomes of measurements, the data. But that supposes that it is clear what the correct theoretical implications, the correct simulation conditions, and the correct data are. By contrast and in reaction to the 'tribunal view' on experiments, this essay will show that experimental activity, first of all, plays an essential role in this task of clarification. It will show the elaboration of an experimental system as an interactive, creative, open-ended process, and highlight its constructive contribution to the processes of modeling and simulating. This constructive role of experimental activity will be explored through the analysis of a particular episode in 20th century fluid mechanics, focusing specifically on two aspects. The first is the identification through experimental activity of the conditions in which the data, that a putative model of the phenomenon would have to fit, can be obtained. These are the conditions which determine what the model will have to account for in order to count as a model of the phenomenon. The second is conceptual clarification. In that episode, a long controversy over the identification of some structural characteristics of the target phenomenon would finally lead to questioning implicit presuppositions about the conditions of measurement. The answer to these questions through experimentation would take the form of a redefinition of concepts central to the understanding of the phenomenon and the conditions of its occurrence.

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[1] The author wishes to acknowledge helpful discussion and correspondence with Paul Teller , Ronald Giere and James Bogen.

1. Wake, frequency and controversy

1.1 The problem

Science provides us or aims to provide us with models of phenomena. For instance: a model of the dynamics of the wake that can be seen in figure 1. This figure shows the wake of a flow behind a cylinder when the velocity of the upstream flow reaches a certain critical value. The cylinder is on the left, seen from above- the flow, going from left to right, is visualized in the plane perpendicular to the axis of the cylinder, and the wake is formed by vortices emitted alternatively on each side of the cylinder and carried away with the downstream flow.

Figure 1: Wake behind a cylinder, seen from above

The formation of such a wake is a very common phenomenon, happening with air or liquid going over a bluff (non-streamlined) body which can be a pole, a rock, an island, and the range of application of a better theoretical understanding of wakes spread from meteorology to the stability of bridges or platforms, from the design of cars and airplane wings to that of helicopters vanes and more generally to all cases of development of periodic instabilities and transitions towards chaotic behavior.

As common as it is and as simple as it looks, this wake, and the attempt to construct a theoretical model of it, triggered an enormous number of studies, and no less controversy. Due to the variety of fluid structures and flow regimes that can be observed in this flow, the flow past a cylinder has served for nearly a century as a model for fundamental studies of external flows and has been characterized as “a kaleidoscope of challenging fluid phenomena” (Morkovin, 1964; Karniadakis & Triantafyllou, 1989)

I will focus on *one,* seemingly simple, question that was the object of a debate involving experimental as well as numerical and theoretical studies in fluid mechanics in the second half of the 20th century. This question concerns the evolution of the shedding frequency of the vortices with the Reynolds number (Re), the dimensionless number representing the velocity of the flow upstream before it reaches the obstacle[2], as Re is increased within a certain interval beyond the critical value: *is the variation with the Re of the shedding frequency a continuous linear variation or is there some discontinuity?*

Again, one should not be misled by the simplicity of the question. The answer to this question is crucial not only to understanding the development of the wake, but also to the general understanding of the development of fluid instabilities with all the applications one can imagine in meteorology or aeronautics. In particular, as we will see, the evolution of the frequency will be suspected of being related to the development of three-dimensional patterns of shedding, which are known to have a direct influence on the tendency for a structure to vibrate in a flow (Miller & Williamson, 1994).

1.2 Modeling, experimenting and relevant parameters

Looking into the details of how this question was answered, we will see a challenge to a common view which reduces the role of experimental activity in the practice of modeling to the assessment of theoretical models. It has been aptly noticed that experimental activity may also have an explorative function. The notion of exploration, however, is vague and may mistakenly suggest a lack of specific direction or constraint in such activity. The function of experimental activity that the following case study will bring to light does not stem from a lack of direction or of constraint, but in contrast to the assessing function, it requires understanding experimental activity as an integral, productive, and creative component of the *construction* of models.

In this constructive function, experimental activity is directed at the identification of the conditions of measurement in which the data in question can be obtained. Experimental activity is here viewed as the place where the structural characteristics of the target phenomenon of the modeling process are specified as such, that is, as what the model will have to account for in order to count as a model of the phenomenon in question at all.

The analysis of this function of experimental activity will call for the introduction of the concept of *relevant parameters*. A parameter is a quantifiable characteristic of the experimental conditions that makes a difference in the outcomes of measurements, and it is a relevant parameter if that difference is regarded as relevant to the understanding of the phenomenon, that is, as having

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[2] The definition of the Reynolds number is $Re = Ud/\nu$ where U is the velocity upstream of the flow, d is the diameter of the cylinder and ν the viscosity of the fluid. For a given fluid and cylinder, increase in Re expresses increase in the velocity upstream.

to be taken into account rather than shielded off. Philosophical studies on experiments have focused on questions of instrumental reliability (Bogen &Woodward 1989), reproducibility, or replicability (Franklin 1986, Radder 2006). But these concerns take for granted the identification of what counts as relevant data, i.e. as data characterizing the target phenomenon, and that a putative theoretical model would have to account for. What will count as relevant data will depend on what is recognized as relevant parameters of the system and relevant parameters do not wear their identity on their sleeves: neither that they are parameters at all, nor that they are *relevant* parameters.

1.3 Separating the problem of relevance

The problem centered on the form of the evolution of the shedding frequency was for a large part a problem of interpretation of outcomes of measurement not only unexpected but in different ways problematic. So our concern is mainly with data, data-models, and the way in which the problems of interpretations they raise are dealt with. But it is not a concern with how a data-model is made out of raw data, that is, how raw data are selected, treated, analyzed, organized with the help of some theories, for instance theories about the experimental conditions or the instruments. First of all, I am not sure what *raw* data could be since I see the making of a data model as a continuous series of procedures starting with the preparation of the experimental set-up and including the measurement procedures. Worse, to stay with that question would still be taking for granted the identification of the experimental conditions of measurement under which the data that are representative of the phenomenon can be obtained. And it is precisely the identification of these conditions that we are here concerned with, together with the identification of the relevant parameters that it implies.

2. Origin of the controversy: the discontinuity

2.1 Experimental studies

The starting point of the difficulties is generally identified with the publication, in 1954, of Anatol Roshko's dissertation "On the Development of Turbulent Wakes from Vortex Streets", a very detailed experimental study of the wake, still a reference in fluid mechanics, which:

1) shows on the basis of measurements (writing "R" for "Re") that "At R = 40 to 150, called the stable range, regular vortex sheets are formed and no turbulent motion is developed", whereas between R = 150 and R= 300 turbulent velocity fluctuations accompany the periodic

formation of vortices.

2) gives, for the stable range, an empirical formula of the linear variation of the shedding frequency with the Re.

These results had been anticipated and were shortly confirmed by other experimental studies. What makes it however, retrospectively, the starting point of the difficulties is that in 1959, a new experimental study of the wake is published that calls into question the adequacy of the distinction between only two ranges of shedding, the stable and the turbulent, and directly contradicts Roshko's results regarding the evolution of the shedding frequency with the Reynolds number.

Regarding the latter point, Tritton (1959), the author of the publication, argues for the existence of a discontinuity in the velocity-frequency curve by showing the "frequency plotted against the velocity for three different runs" (see figure 2). He recognizes that "the discontinuity does not come in just the same position relative to the points each time" and he recognizes that "if all the runs were shown on a single Reynolds number vs Strouhal number plot [frequency] the discontinuity would probably not be apparent" but takes that to be the reason why "it has not been noticed by other workers". (566)

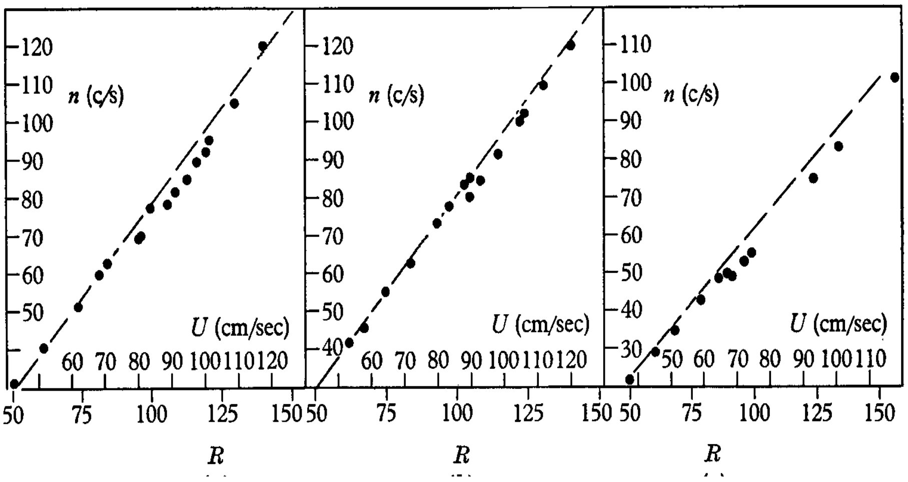

Figure 2: Variation of the frequency of shedding with the Reynolds number for three different runs . The dots represents Tritton's experimental results whereas the broken line is given by Roshko's formula (JFM, 1959, vol.6)

Regarding the former point, the distinction between two ranges of shedding, one stable the other turbulent, Tritton argues, on the basis of visualizations of the wake that had not been made by Roshko, that the dynamics of the wake is not what Roshko's identification of the main ranges of shedding suggested. Beyond the discontinuity, that is, for values of Re greater than the one for which the discontinuity occurs, the shedding of the vortices along the cylinder is not simultaneous or, to put it differently, the lines of vortices, imaginary lines joining side by side vortices along the cylinder, are not parallel to the axis of the cylinder; they are oblique (figure 3). What's the problem with that?

2.2 The conflict

Roshko's simple distinction between two ranges of shedding suggested that the dynamics of the wake in the stable range would be two-dimensional, contained in the plane perpendicular to the cylinder. "In the stable range", he wrote, "the vortex street has a periodic spanwise structure" (1954:1), suggesting that the vortices emitted on the same side of the cylinder are emitted simultaneously and that the line of vortices, if observed, would be parallel to the axis of the cylinder. That the successive lines of vortices are or are not parallel to the axis of the cylinder translates in terms of the dimension of the dynamics of the wake: parallel lines of vortices correspond to a 2-dimensional dynamics of the wake, whereas non-parallel lines of vortices testify to the existence of a dynamics in the direction of the cylinder, which added to the 2-dimensional dynamics would make the total dynamics of the wake 3-dimensional. But 3-dimensional effects on the dynamics were thought to be associated with the development of turbulence, which according to Roshko took place beyond the stable range.

Figure 3: Oblique shedding of the vortices behind the cylinder for Re>90 - The cylinder is the black band on the left. (JFM, 1959, vol.6)

This conflict between Roshko's and Tritton's experimental results will start a controversy of 30 years about *"whether the discontinuity [and the oblique shedding] is an intrinsic, fluid-mechanic phenomenon, irrespective of the experimental set-up"*. And it is the way in which this controversy developed and was resolved that I am about to analyze. I am here quoting Williamson (1989), one of the participants in the debate. More than just a participant, he will here be given the last word on the issue- although , in science, just like in philosophy, the last word is generally not the last for very long

3. Conflicting interpretations of the discontinuity

Numerous publications followed those by Tritton and Roshko arguing for one side or the other. Rather than giving an exhaustive account of the literature, I will focus on studies which offered original explanations of the observed discontinuity, presenting evidence for these explanations, and often motivating, in their turn, new sets of experimentation and arguments. What is philosophically remarkable when one looks at the panel of explanations and supportive evidence that were advanced is that they pretty well exhausted the different forms of justification of the reliability or significance of experimental observations, like reproducibility, replicability, controlled and quantifiable modification of the observed effects, without however being able to put an end to the polemic.

The reason , as I will show, is that some basic questions about the specification of the conditions of measurement had first to be explicitly addressed and answered. To address and answer these questions will result in the refinement and sometimes even redefinition of concepts central to the understanding of the phenomenon and the conditions of its occurrence.

3.1 Claim: The discontinuity is an artefact

In 1969, Tritton's claims for a nonlinear evolution of the shedding frequency were objected to on the basis of new experimental results supporting an explanation of the discontinuity and the 3-dimensional effects in terms of effects of non-uniformities. The main sources of non-uniformities were identified as being the upstream flow and irregularities in the diameter of the cylinders. Experiments conducted by Gaster (1969) showed that increasing artificially the non-uniformities in the flow, or irregularities in the cylinder diameter, had the effect of increasing the discontinuities and in fact generated additional discontinuities.

Reducing the span of the cylinder will have the corollary effect of reducing the amount of irregularity along the cylinder. Gaster could then feel comforted in his explanation by the observation that reducing the span of the cylinder had indeed the effect of suppressing the 3D dynamics along the cylinder, allowing a parallel shedding, with lines of vortices parallel to the axis of the cylinder. These results strongly suggested that the discontinuities and the 3-dimensional effects presented by Tritton as features of the wake should rather be regarded as an artefact of the experimental set-up.

Tritton had supported his argument by the reproducibility of the discontinuity. But if the non-uniformities to which Gaster attributes the generation of discontinuities are present in all the set-ups used by Tritton, then this reproducibility is exactly what one would expect.. By showing the influence on the measurements and observations of a basic characteristic of the experimental set-up, Gaster thus countered Tritton's argument from reproducibility. Or so it could seem. Gaster's results related to the effect of the length of the cylinder would prove significant, but their significance would actually be quite different from what he thought.

3.2 Claim: The discontinuity is not an artefact

In 1971, new studies were made by Tritton with both water and air tunnels so as to ensure a better control of flow non-uniformities, and again he argued in favor of the 'reality' of the discontinuity. He then proposed to understand the discontinuity as a transition between two distinct instabilities requiring two different explanations of the development of the wake but without offering more to support their existence than the need to account for the discontinuity and without saying more about these explanations than what could be observed in the experiments.

This did not prevent new experimental arguments for the opposite interpretation of the discontinuity, this time as resulting from micro-vibrations of the cylinder itself as the velocity of the flow increases (van Atta & Garib, 1987). Tritton's explanation probably seems too ad-hoc to be right. But, on the other hand, that new discontinuities arise with an increase of non-uniformities doesn't show that without non-uniformities there would be no discontinuity. The observations made when the length of the cylinder is reduced seem to partly fill the gap: not only are there more discontinuities when there are more non-uniformities, but there are less discontinuities when there are less non-uniformities. However, even that is not as compelling as it seems: it is too hasty in identifying reduction of the length with reduction of the non-uniformities in the value of the diameter. It would turn out that another interpretation could be given of the relation between length and mode of the shedding vortices.

And finally, importantly, no attempt to attribute the origin of the discontinuity to some aspects of the experimental set-up yielded a convincing account of the specific value or range of values of Re at which the discontinuity appears. That was one of Tritton's strongest points for requiring an explanation in terms of development of instabilities involving the specification of a threshold for the growth of the instability.

4. Enter the Landau model

4.1 Model implications vs experimental measurements

It is not until 1984 that a model of the wake was proposed to account for its temporal dynamics, i.e. the temporal evolution of the amplitude of the vortices and of the frequency at which they are emitted (Mathis & al., 1984). The model in question is obtained by applying to the wake situation the general model proposed in 1944 by Landau to describe the development of a periodic instability --which he viewed as the first step towards turbulence. It was then introduced as ‘the Landau model of the wake’:

$\mathbf{dU_y/dt = (\sigma_r + i\sigma_i)U_y - (l_r + il_i)\ |U_y|2\ U_y}$ where U_y is the complex amplitude of the wake, and $(\sigma_r + i\sigma_i)$ and $(l_r + il_i)$ are resp. the linear and non-linear coefficients.

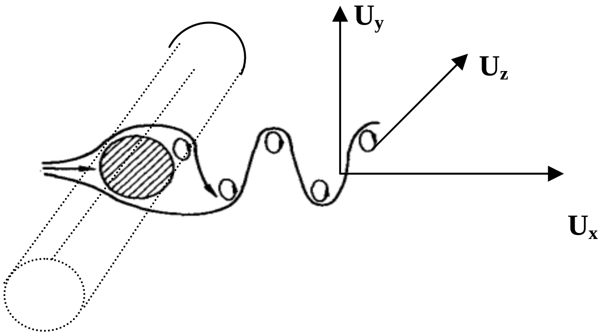

Figure 4: Diagram of the experimental geometry

From this model can be derived the evolution of the real component of the amplitude of the instability with the control parameter, here the Re, and its critical value Re_c

$U^2_{ymax}\ (=\sigma_r/l_r) \propto (Re - Re_c)$

The experimental results show that, regarding the evolution of the amplitude, the model works beautifully- even better than expected. So for the evolution of the amplitude, at least , one and the same model can account for the development of the instability on the whole range of the Reynolds number.

But so far this applies only to the evolution of the amplitude and the real test will be with the evolution of the frequency with Re. The relation that can be derived from the model shows a linear variation of the frequency with Re. If that was the case as well , Tritton’s claim that two different instabilities are at play would be shown to be false. When the measurements are made, however, what they show is the existence of a discontinuity (see figure 5). And additional measurements made along the cylinder indicate the existence of a 3-dimensional dynamics, an oblique shedding.

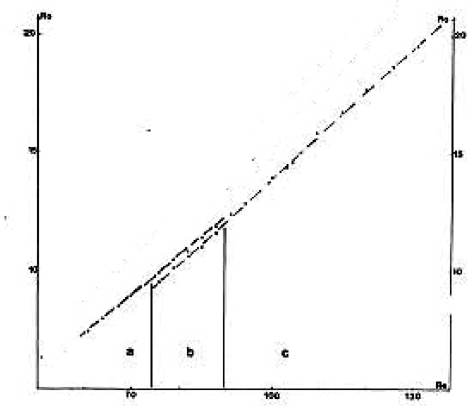

Figure 5: Experimental results of the evolution of the frequency with the Re

4.2 Interpreting the result of the comparison

Question: Does the discrepancy between the model's prediction of the evolution of the frequency and the outcomes of measurement show or even indicate that the Landau model is not an adequate model for the wake?

It will depend on whether that discontinuity has to be accounted for by a model of the wake. The model of the wake not only doesn't have to account for it, but should not account for it if the discontinuity is an artefact . On the other hand, if it is considered to be an intrinsic feature of the wake, a model that does not account for it cannot, in that context, count as a model of the wake.

Ronald Giere writes that "If what is going on in the real world is *similar in structure to the model* of the world then the data and the prediction from the model should agree". (Giere 2006, 30) The obviousness of this claim is only apparent. The problem is not that there is no absolute definition of what counts as agreement or lack of agreement between the data and the prediction. Even if we assume contextual agreement on what counts as agreement between model's prediction and data, it has to be decided what the data are that Giere is referring to. As the example of the wake and the controversy over the discontinuity shows, it is not always clear what the data are that the model should agree with and not easy to identify them as such.

Hence the problem is not that of data analysis or of how scientists construct what is usually referred to, after Suppes (1962), as 'models of the data'. The problem we are presently focusing on is prior to that of the treatment of the data. Even if some procedures of analysis are assumed to be in place, and a data model is produced, like the data-model of the evolution of the shedding frequency with Re, we are still left with the open question of whether this data-model is one that the model of the wake should agree with.

5. Intrinsic characteristics and relevant parameters

The predictions of a theoretical model of the wake will have to agree with the data only if these data are informative about the features of the wake that the theoretical model aims to provide information about, instead of being non-informative or maybe even misleading, as an artefact is. Just as the theoretical aim is not just any theoretical model but a theoretical model of the dynamics of the wake, so it is not just any data-model but a data-model of the dynamics of the wake that experimental measurements aim at.

As quoted above, Williamson described the controversy as a search to determine *'whether the discontinuity is an intrinsic, fluid-mechanic phenomenon, irrespective of the experimental set-up'*. The idea of being irrespective of the experimental set-up seems to offer an empirical criterion to distinguish genuine data, ones that are informative about the target phenomenon, from non-informative data, including artefacts. If the discontinuity is intrinsic it should not depend on the experimental set-up, so if it is shown to depend on the experimental set-up, then it is not intrinsic. This is obviously what motivated the experimental studies of the effect of an increase of the non-uniformities in the flow or in the diameter, as well as of the effect of making a cylinder vibrate. In each case, the idea is to show that the discontinuity is generated by some specific features of the experimental set-up and consequently is not a feature of the wake itself.

It is not sufficient, however, to show that the discontinuity is only the effect of non-uniformities or vibrations. For that, it should be shown that without non-uniformities or vibrations, there is no discontinuity. That was indeed, as we will see, the challenge that some numerical studies were going to try to address.

But the notion 'irrespective of the experimental set-up' raises a fundamental question that will prove crucial to the interpretation of the simulations that were carried out. "Irrespective of the experimental set-up" cannot be taken to mean "completely independent" of the characteristics of the experimental set-up. After all, the shedding itself does depend on the value of the velocity of the upstream flow, and other characteristics of the experimental set-up, like the diameter of the cylinder or the viscosity of the fluid, do influence the dynamics of the wake. The influence of these measurable characteristics will be part of our understanding of the wake; they will be taken into account through the Reynolds number, a control parameter of the system. The effect of a change in value of Re counts as an intrinsic feature of the wake and has to be accounted for by a model of the wake. The Reynolds number is therefore a *relevant parameter* of the system.

To regard, by contrast, the effect of non-uniformities, or vibrations of the cylinder, not as intrinsic but as artefacts is to regard these effects as not having to be accounted for, and to regard the source of these effects, non-uniformities or the vibrations, as not having to be taken into account by a model of the wake.

6. Simulation of the wake

To demonstrate that there are more discontinuities when the non-uniformities and vibrations are increased is not enough, as we saw, to show that the discontinuity is merely an effect of non-uniformities or vibrations of the cylinder, and therefore is an artefact. What should be shown is that when there is *no* non-uniformity or *no* vibration, there is no discontinuity. But this is not an easy thing to show. A flowing fluid as well as the diameter of a cylinder keeps a certain level of non-uniformity however carefully they are prepared. This is where one would like to make a thought experiments starting with 'imagine a flow with no non-uniformities…'. Fortunately, the situation of the wake, by the end of the eighties, lent itself to the modern alternative: the numerical simulation, which one should think will be less subject to ambiguous interpretation. But one may well be wrong. The problem lies with how the line is drawn that separates the characteristics of the experimental set up qualifying as relevant parameters from the others.

6.1 What the simulation shows

A simulation of the equations of Navier Stokes (NS), fundamental equations in fluid mechanics, was performed and the results of the simulation were presented as pointing to a definite answer to the question of the nature of the discontinuity (Karniadakis & Triantafyllou, 1989)

The result of the simulation shows how a flow, whose dynamics is governed by NS, develops when there are no non-uniformities of any sort and no vibration; and the answer was that the evolution of the frequency with Re is linear, with no discontinuity.

That the discontinuity doesn't appear in the results of the simulation indicates that its occurrence in the experiments results from the influence of some characteristics of the experimental conditions that are not taken into account as parameters of the system in NS. But the parameters of NS are those the effect of which is constitutive of fluid-mechanical phenomena. So, if one trusts the method used for the simulation (a spectral-element method, used successfully in previous studies) and does not envisage calling into question the validity of the equations, it is most likely that whatever difference these characteristics may make in the experimental outcomes will have to be regarded as an artefact and will have, consequently, to be shielded off[3].

6.2. Interpreting the results of the simulation

This reasoning regarding what the simulation shows about the discontinuity only holds, however, if what is simulated is really the same phenomenon which was the target of the measurement showing the discontinuity in the evolution of the frequency. When one speaks of simulating the fundamental equations, this is not exactly right; actually it is rather far from being right. The fundamental equations hold for many very different kinds of situations. Going from the fundamental equations to the simulation of a target phenomenon must therefore involve each time some crucial specifications that determine what situation is simulated.

A closer look raises doubt as to the significance of the result of the simulation regarding the problem we were concerned with. The geometry of the simulated situation is 2-dimensional (figure 6): it corresponds to a flow contained in a plane corresponding, in the real situation, to a cross section of the cylinder.

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[3] What counts as artefact is of course relative to the definition of the target of the experimental investigation. Instruments are the most common source of artefacts; for instance a hot wire anemometer is normally used to measure the velocity of a fluid, but is sensitive to the temperature of the flow, so a changing temperature will make a difference in the outcome of measurement, and that is an artefact of the instrument. If vibrations of the cylinder were shown to have an effect on the outcome of measurement of the frequency, it would be regarded as an artefact if the target of the measurement is the ‘fluid mechanics phenomenon’ of development of the wake. But the effect of the vibrations of the cylinder on the development of the wake is also a common subject of study; there the phenomenon is that of aeroelastic coupling between the vortex street and the cylinder vibrations, and the effect of the vibrations is what is measured.

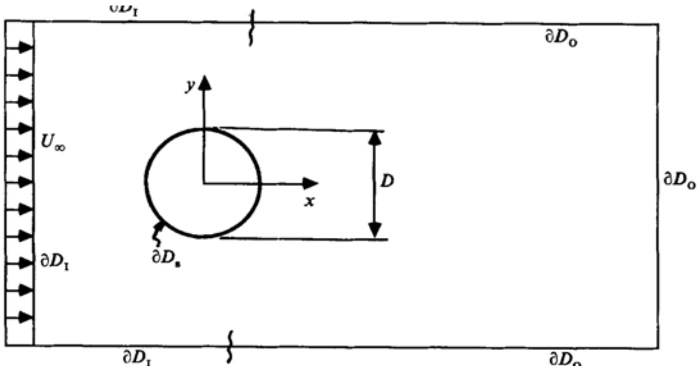

Figure 6: Geometry definition for the simulation

So how could this simulation of the development of a flow in a 2-dimensional plane be taken to correspond to the case of a flow going around a cylinder? In the latter case, the flow develops in a space which contains not only the plane perpendicular to the axis of the cylinder but also the plane which contains the axis of the cylinder!

There is an answer to this question: suppose that, with respect to the phenomenon of study, the wake, all points on the cylinder are equivalent to one another, that there is no way to distinguish what happens at one point from what happens at another point. Then, no need to simulate the wake in each point of the cylinder since what happens at any cross section will be identical to what happens at all of them. The 2D simulation shows then how the wake develops, according to NS, in conditions where all the points on the cylinder are interchangeable. But why should we think that all the points are interchangeable? The presence of the ends obviously create an asymmetry contradicting the assumptions of the simulation!

To this question too there is an answer: suppose that a cylinder that is long enough can be regarded as infinite, and that an infinite cylinder can be regarded as cylinder that has no end. If there is no end, then we are in the situation where all points are interchangeable. All that is needed to satisfy this assumption of an infinite cylinder is that, for a long enough cylinder, what happens in the middle part of the cylinder be independent from what happens at or near the ends. And it can be then admitted that the two-dimensional simulation will, at least, show what should happen, according to Navier-Stokes, in a long enough cylinder, far enough from the ends.

Taking the simulation as relevant is, consequently, taking the ends of the cylinder as not being relevant to the understanding of the fluid mechanical features of the wake, amplitude or frequency. *The ends are then not taken to be a relevant parameter of the system.*

7. Experimental contribution to conceptual understanding

The applicability of the results of the simulation rests on the assumption that the effects that the ends of a cylinder of finite length may have on the dynamics of the wake are not intrinsic characteristics of this dynamics. This assumption may seem to be supported by some measurements that have shown that for a cylinder that is long enough, the frequency of shedding in the middle of the cylinder is different from that found near the ends of the cylinder. But that should not mislead us into thinking that the assumption is an empirical assumption. Discrepancies between the results of the simulations and the results of the measurements sometimes serve as a basis to modify some parameters of the simulation model in the search of better agreement with the phenomenon. (Lenhard, 2007) This is not the case here.

The simulation has rather a normative function. It implies, in effect,

- that the normal conditions of development of the wake, where it has its ‘pure’ form, are those where the cylinder is like one with no end. It follows from this that conditions under which the ends would have an effect on the measurements would not count as right conditions of measurement, those under which *only* the relevant physical characteristics of the experimental set-up have an effect on the outcome of the measurement and under which a data-model of the phenomenon can be obtained.

- that the distinction between cylinder with end and cylinder like one with no end hinges on the length of the cylinder. The ends of the cylinder are here treated in the same way as non-uniformities of the flow or vibrations of the cylinder: if they have an effect on the outcomes of measurement this effect will be classified as artefact and should be shielded off. The way to shield it off, it is assumed, is to have a sufficient length.

These implications will be called into question in Williamson 1989, a scrupulous and thoroughgoing experimental study of the evolution of the shedding frequency of the wake, that was a turning point on the issue of the discontinuity and the development of 3-dimensional effects.

7.1 Checking the influence of the non-uniformities

To begin with, Williamson carried out a series of measurements directed at testing the attribution of the discontinuity and 3-dimensional effects to the existence of non-uniformities or vibrations. “[A] good deal of effort was taken to isolate the cylinders from the tunnels and to damp out any cylinder vibrations” (584) and in order to monitor any possible vibration a vibration detector was set up. The discontinuity is observed, and again only for a particular value of the

Reynolds number, which remains the same for cylinders of different diameters. On the basis of these results, and other measurements comparing the spectra of the wake and of the cylinder vibrations, the author eliminates the vibrations as explanation of the discontinuity.
Regarding the non-uniformities, the set-up allows for a “level of turbulence close to 0.1% with flow uniformity better than 0.3%”, which are lower rates than those usually obtained. Still, 0.1% is not the same as no non-uniformities at all. More convincingly, similar results are obtained as well when ‘the cylinder is towed through the quiescent fluid” (instead of being fixed in a moving flow), in which case “the flow incident on the cylinder is likely to be particularly uniform”.

7.2 Checking the influence of the ends

The next and main part of the investigation focuses on the study of the influence of the ends of the cylinder.

To begin, it is found difficult to obtain repeatable measurements without the use of endplates, little disks fixed at the ends of the cylinder perpendicular to the axis of the cylinder, to shield the span of the cylinder from the boundary layer along the test-section walls. The author sees the need for endplates as ‘an early demonstration of the importance of the end conditions of the flow across even large spans”. (585)

Secondly, measurements of the shedding frequency with a probe moving along the span of the cylinder show the existence of different regions characterized by different shedding frequency. In particular, there exists near the ends a region of lower frequency, baptized ‘end-cell’ by the author. For a cylinder with an aspect ratio (the ratio L/D of the length to the diameter) superior to 45, the frequency in the central region of the span is different from the end-cell frequency and remains unchanged as L/D is further increased. “This suggests”, Williamson writes, “that the vortex shedding in the central regions of the span is unaffected by the *direct* influence from the end conditions” (590) Note however, it will be of crucial importance, that Williamson only recognizes the absence of a *direct* influence.

For smaller values of the aspect ratio, the frequency of shedding is found everywhere the same as that found near the ends, as the size of these regions is now sufficient to cover the whole span. Remember that Gaster interpreted the reduction of the span of the cylinder in terms of reduction of the non-uniformities of the diameter and took that to be the explanation for the shedding being parallel in this condition. Williamson will propose the existence of a single frequency over the whole span as alternative explanation. But before getting there, another set of measurements and observations is still needed, leading to a new conceptual understanding of the notion of ends, independent of the notion of length, and to the inclusion of the ends among the relevant parameters of the system.

7.3 Redefining the notion of ends

Why did Williamson underline the absence only of a *direct* influence of the ends on the wake in the central region? The visualizations of the development of the wake show that, initially, the vortices are shed parallel to the cylinder, and that progressively the parallel pattern is transformed into a stable oblique pattern which propagates from the ends of the cylinder towards the central region. These observations suggest that the ends influence the way in which the wake develops in the central region. But even if that is the case, in itself, that only shows that the ends can influence the development of the wake, nothing more. The decisive measurements and observations in favor of a new conception of the ends, their role, and consequently the wake itself are still to come.

Remember the endplates added at the ends of the cylinder. So far, all the observations and measurements had been made with endplates *perpendicular* to the axis of the cylinder, in the same way as in previous experimental studies. Intrigued by the effect of the ends of the cylinder on the development of the wake, Williamson decides to manipulate the end conditions by changing the angle between the axis of the cylinder and the plates. He then realizes that "if the leading edge of the endplates were angled inwards by 12 degrees or greater, then parallel shedding was induced". As figure 7 shows, for a certain angle, the shedding becomes parallel, i.e., two-dimensional, and the discontinuity disappears even though *the length did not change*.

The explanation is that the regions of lower frequency at the ends of the cylinder generate the propagation of a phase difference towards the central region which creates the pattern of oblique shedding. Changing the angle of the plates has the effect of changing the *pressure* conditions responsible for the lower frequency towards the ends. For a certain interval of angles of the endplates, when the pressure and the vortex frequency match those values over the rest of the span, there is no propagation of phase difference, and the shedding is parallel; for a different interval of angle, the shedding is oblique. And the discontinuity only appears in the oblique mode of shedding and is found to correspond to the transition of one oblique pattern to another with a slightly different geometry.

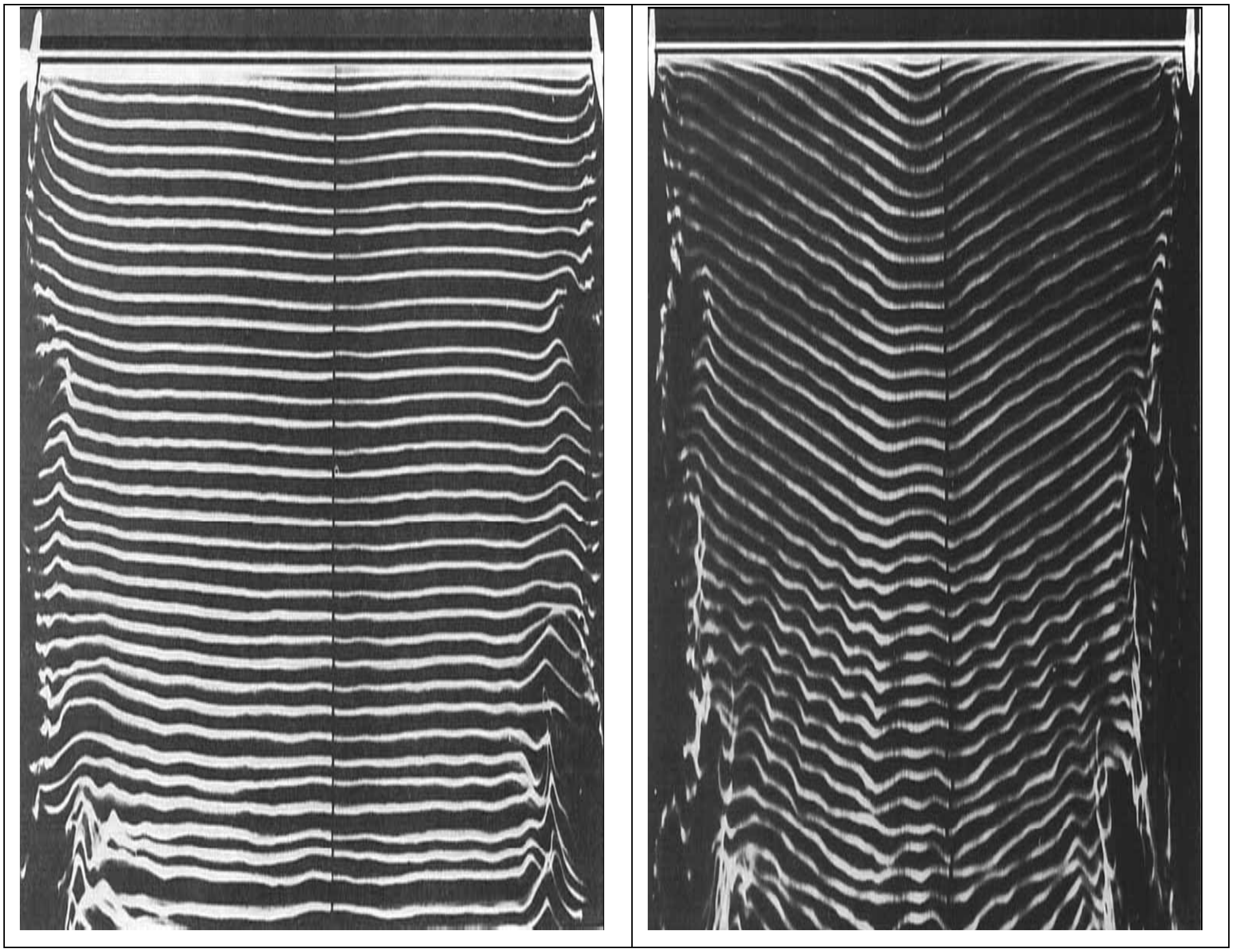

Figure 7: Photos of the wake behind a cylinder (top of the photos), seen in the plane containing the cylinder. Note the plates at the ends of the cylinder. Depending on the angle of the plates, the lines of vortices are parallel or oblique. (JFM, 1989, vol.206)

7.4 New relevant parameter and reconception of the wake

Williamson takes his results to "show that [the oblique and parallel patterns] are both intrinsic and are simply solutions to different problems, because the boundary conditions are different". In effect, the two forms of shedding simply correspond to different values of the angle between the endplates and the axis of the cylinder. Since there is no reason to give a special status to certain values of this angle, there is no reason to take only one of the shedding pattern as being normal or intrinsic. In this new perspective, the parallel and the oblique pattern are not two distinct phenomena with only one being the normal form of the wake, but two possible configurations of the flow corresponding to different values of a parameter of the experimental system, two possible solutions for the same system in different conditions.

But this new way of seeing things supposes that a new parameter be added to the set of relevant parameters of the system; a parameter that characterizes the end conditions of the cylinder. This parameter is independent of the length of the cylinder. The concept of end has been redefined in terms of pressure difference and value of the angle of the end plates that determined the value of this pressure difference. And the effect that the end conditions have on the development of the wake is now part of the structural characteristics of the wake. By integrating this parameter among the set of relevant parameters the gain is one of conceptual unification: what were seen as two distinct phenomena have been unified under the same description.

Conclusion

In 1991, in reaction to the redefinition of the role of end conditions and reconception of the wake subsuming patterns both of parallel and oblique shedding, a new model was proposed [Albarede & Monkewitz, 1991] obtained by adding to the Landau model a term of diffusion along the spanwise direction. The simulation of this new model was able to display the phase dynamics that Williamson's experimental study had finally raised to the rank of intrinsic feature of the dynamic structure of the wake. Already, however, the exactitude of some of Williamson's measurements was called into question on the basis of an analysis of the solutions of this model. New measurements were to follow, and new simulations, and a modified version of the model, and so it goes on.

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