Control engineer and much more: aspects of the work of Aurel Stodola

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Introduction

In 1976 a brief article appeared in the *ASME Journal of Dynamic Systems, Measurement and Control* outlining the contribution of a certain Aurel Boleslaw Stodola (Figure 1) to the development of control theory.[1] Stodola was Professor of Mechanical Engineering at the *Polytechnikum* in Zurich (subsequently the Swiss Federal Institute of Technology) from 1892 until his retirement in 1929. For control engineers, he deserves to be remembered chiefly because he drew the attention of a mathematician colleague to the need for a stability criterion; the mathematician was Adolf Hurwitz, and the result of Stodola's approach was the Hurwitz version of the Routh–Hurwitz test, published in 1895. Apart from the aforementioned article, however, and a section based upon it in Bennett's *History of Control Engineering*,[2] there seems to have been little written about Stodola's work in the control literature. During a recent visit by the author to the Swiss Federal Institute of Technology, Zurich, the opportunity was taken to look through relevant archive material. The picture of Stodola which emerged is of a fascinating personality. In addition to his early achievements in control engineering, he carried out fundamental work in turbine and compressor design (with which readers from a fluid engineering background may well be familiar), and he was also in contact with many of the great names of early 20th century science and technology: correspondence is extant with Einstein, Planck, Polya, Von Mises, and others.

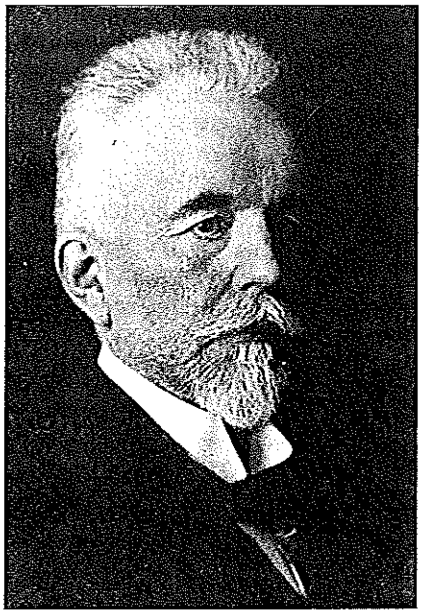


Fig 1 Aurel Boleslaw Stodola 1859–1942

Stodola's role in the development of the Hurwitz criterion has now been documented in detail elsewhere[3]; the aim of this article is to present a more rounded description of his achievements. Although the emphasis will naturally be on Stodola's contributions to control engineering, rather than to steam or gas turbine development, some other aspects of his work will also be considered, notably the views expressed in his most unusual 1931 publication entitled *Thoughts on the Philosophy of an Engineer.*

Turbine regulation

In the years immediately following his professorial appointment, Stodola devoted considerable time to the analysis and design of control systems. Work on turbine regulation ultimately led to the Hurwitz criterion, but his interest in prime mover governors also led him to investigate other aspects of control system dynamics in a detail quite unusual at the time.

*The stability criterion**

In 1893, Stodola published an analysis of the dynamics of a hydraulic turbine relay control system,[4] emphasising the stability problem, and basing his analysis on earlier continental work. The system model was third-order, so the conditions for closed-loop stability based on a differential equation were straightforward to obtain, and had been found both by Maxwell in his 1868 paper 'On governors' and by the Russian engineer Vyshnegradskii. (The latter's work had appeared in both French and German, and so was well-known in continental Europe; *see* refs. 2 and 3 for a discussion of the background). Stodola's major achievement in his 1893 study was the introduction of time constants and dimensionless numbers. After deriving three simultaneous first-order differential equations modelling the system, he replaced the coefficients of the derivative terms by the constants:

> T_1, T_2, T_3, with the dimensions of time, whose mechanical significance is easy to deduce from the corresponding expressions. In particular, T_1 is a measure of the rotating mass, . . . T_2 is a measure of the penstock length, T_3 is a measure of the size of the surge chamber . . .

Similarly, dimensionless numbers were introduced which were also measures of important physical effects such as friction.

Simplifying the equations in this way was, of course, much more than just an aid to algebraic manipulation. Time contants allow specific equations to be interpreted immediately in a physically meaningful way, and have remained an essential modelling tool in system dynamics, along with other normalizing concepts such as damping ratio and natural frequency. Stodola well appreciated the advantages of time constants, and carried out his stability analysis in such terms; his design relationships were expressed as restrictions on the relative magnitudes of the various time constants and dimensionless numbers, rather than in terms of turbine runner mass, pipe lengths and so on. This detachment of system characteristics from the detailed physical construction of engineering devices was an important step towards the 'systems approach' which later became standard.

In order to limit the system to third-order, certain simplifying assumptions had been made, such as neglecting the inertia and damping of the controller mechanism. By relaxing these restrictions, however, the order of the system increased, and a general method was needed to assess stability in place of the Vyshnegradskii technique, which applied to third-order systems only. At some point in 1893, therefore, Stodola referred the problem to Adolf Hurwitz (Figure 2), a mathematician colleague at Zurich. (Both Stodola and Hurwitz were, of course, unaware that Routh had already solved the problem in 1877[5].) By early January 1894 Hurwitz had found an ingenious solution, and on the 7th of that month Stodola wrote to

Fig 2 Adolf Hurwitz 1859–1919

him expressing his gratitude for 'the inspired solution to the root problem which has so tormented me'. In April that year, Stodola was therefore able to publish an extended treatment of turbine stability, in which a seventh-order system was analysed, and the Hurwitz criterion was stated for the first time.[6] This statement of the Hurwitz stability criterion (Figure 3) preceded the publication of the proof[7] by over a year. Indeed, by the time the derivation appeared, Stodola had used the criterion again in the design of a control system, this time in connection with the turbine installation at Davos Spa.

It was particularly significant that the Hurwitz criterion first appeared in an engineering journal: the *Schweizerische Bauzeitung* (*Swiss Construction Engineering Journal*). Unlike the Routh counterpart in the English-speaking countries, by the first decade of the 20th century the Hurwitz criterion, together with Stodola's approach to system modelling, had found its way into standard treatments of prime mover regulation within the German-speaking parts of Europe.

The inertia governor

Although aspects of turbine control featured in Stodola's later work from time to time, these, as Profos[1] points out, were predominantly application studies with little significance for the development of control engineering as a discipline. One more fundamental paper, however, is a detailed treatment of the so-called inertia governor, published in 1899.[8]

In a conventional (proportional) centrifugal governor, response to a load variation could be sluggish, since the control action increased only slowly as the engine speed began to deviate from its nominal value. In the inertia governor, control action was increased during this early period by sensing the *acceleration* of the motor in addition to its speed: to use modern terminology, it was a proportional + derivative controller.†

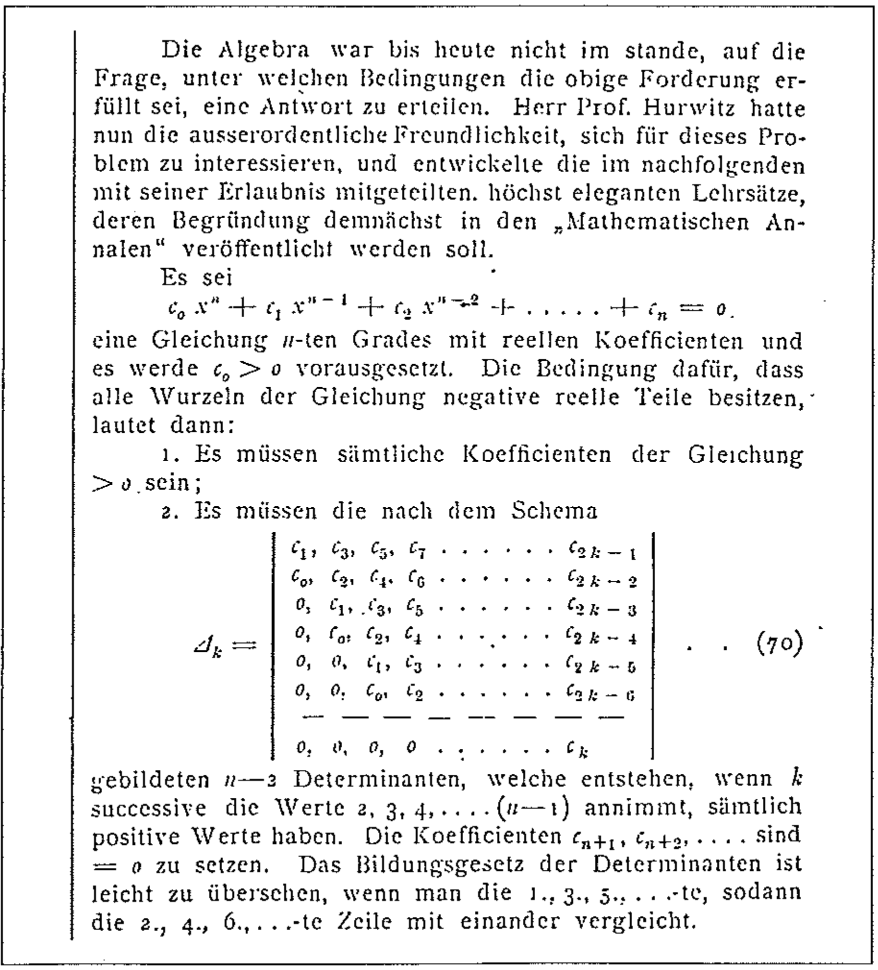
Stodola's illustration of the principle of the inertia governor is shown as Figure 4. In the steady state, the mass *J* rotates with the same angular velocity as the shaft *A*. A change in speed (acceleration or deceleration) of *A* is quickly transformed via the gearing *BCD* into a force on *E* (rather as in a seismic mass accelerometer). The resulting movement is used, via the toothed segment *F*, the gear *G* and shaft *H*, to provide an extra (derivative) component in the control action in addition to the normal proportional governor action. Stodola himself summed it up succinctly (ref. 8, p. 507):

> Briefly, this new principle is as follows. The accelerating force (or its opposite) arising from a change in load, and acting on a freely rotating mass (in other words, the inertial resistance of the auxiliary mass) is used to adjust the position of the control member of the engine.

Before reviewing various commercial designs of inertia governor – a device which had become widespread, particularly in the United States, towards the end of the nineteenth century – Stodola gave a thorough analysis of its dynamic behaviour. Particularly noteworthy were its stabilising properties. One of the major difficulties of governor design had been the elimination of offset, since governors which attempted to achieve this were prone to instability, owing to their inherent integral action. The stabilising effect of the derivative action of the inertia controller, however, rendered the use of governors without offset (known in the German literature as *astatic* governors) quite feasible (ref. 8, pp. 511-512):

> The inertia controller allows a fully astatic or even a completely unstable governor to be used . . . Stability can be achieved even in the latter case by providing sufficient damping and a large enough inertial mass. . . . In the absence of inertial action, however, stability demands a static governor (one with offset).

Clearly, then, Stodola recognised many



Die Algebra war bis heute nicht im stande, auf die Frage, unter welchen Bedingungen die obige Forderung erfüllt sei, eine Antwort zu erteilen. Herr Prof. Hurwitz hatte nun die ausserordentliche Freundlichkeit, sich für dieses Problem zu interessieren, und entwickelte die im nachfolgenden mit seiner Erlaubnis mitgeteilten. höchst eleganten Lehrsätze, deren Begründung demnächst in den „Mathematischen Annalen" veröffentlicht werden soll.

Es sei

$$c_0 x^n + c_1 x^{n-1} + c_2 x^{n-2} + \ldots\ldots + c_n = 0.$$

eine Gleichung n-ten Grades mit reellen Koefficienten und es werde $c_0 > 0$ vorausgesetzt. Die Bedingung dafür, dass alle Wurzeln der Gleichung negative reelle Teile besitzen, lautet dann:

1. Es müssen sämtliche Koefficienten der Gleichung > 0 sein;

2. Es müssen die nach dem Schema

$$\Delta_k = \begin{vmatrix} c_1, & c_3, & c_5, & c_7 & \ldots\ldots & c_{2k-1} \\ c_0, & c_2, & c_4, & c_6 & \ldots\ldots & c_{2k-2} \\ 0, & c_1, & c_3, & c_5 & \ldots\ldots & c_{2k-3} \\ 0, & c_0, & c_2, & c_4 & \ldots\ldots & c_{2k-4} \\ 0, & 0, & c_1, & c_3 & \ldots\ldots & c_{2k-5} \\ 0, & 0, & c_0, & c_2 & \ldots\ldots & c_{2k-6} \\ - & - & - & - & - & - \\ 0, & 0, & 0, & 0 & \ldots\ldots & c_k \end{vmatrix} \quad . \quad . \quad (70)$$

gebildeten $n-2$ Determinanten, welche entstehen, wenn k successive die Werte 2, 3, 4, ... $(n-1)$ annimmt, sämtlich positive Werte haben. Die Koefficienten $c_{n+1}, c_{n+2}, \ldots$ sind $= 0$ zu setzen. Das Bildungsgesetz der Determinanten ist leicht zu übersehen, wenn man die 1., 3., 5., ...-te, sodann die 2., 4., 6., ...-te Zeile mit einander vergleicht.

Fig 3 First statement of 'Professor Hurwitz's most elegant theorem' on conditions under which characteristic equation has no roots with negative real parts. Stodola explains how to set up Hurwitz determinants for given polynomial; stability criterion is that all n-2 determinants constructed from the coefficients must be positive[6] of the classic features of proportional, derivative and integral action, although his conclusions were not expressed in such modern terms. His paper went on to analyse dynamic behaviour in detail, including transient response. By the end of the century demands on control system transient performance could be quite stringent. A typical requirement in a power generation plant, for example, was to restrict speed variation to 3% in response to a load variation of 30%. Such a specification required careful governor design, and Stodola concluded his paper with design charts, a description of their use, and a comparison of various American and European governors.

Taken as a whole, Stodola's contribution to the early development of control engineering was substantial. His role in the formulation of the Hurwitz criterion, and his promulgation of a clear approach to mathematical modelling (later taken up by other writers), did much to establish a common approach to the control of prime movers in those countries where his work was known. In many ways, he could be viewed as the first 'control engineer' (without attempting to define the term!); earlier work on governors can be more accurately categorised perhaps as mechanical engineering, scientific instrumentation, etc. By the turn of the century, however, Stodola's major interest had become the prime movers themselves, rather than their control systems.

The turbine design engineer

Stodola first made his name in steam turbine engineering as a result of a paper presented to the Dusseldorf meeting of the VDI (the German engineers' professional body) in 1902. It aroused so much interest that it formed the basis of the first edition of his book on the subject in the following year.[9] *Steam Turbines*, later extended to embrace gas turbines and ultimately centrifugal compressors, was translated into French and English, went through six editions, and became a standard text. In it, Stodola dealt with principles of thermodynamics, gave a thorough treatment of fluid flow within a turbine, and analysed many important stress and vibration problems. Among Stodola's major innovations were the introduction of the gas-entropy chart and the application of the Lanchester–Prandtl theory to the air flow in centrifugal compressors. Stodola was also in great demand as an industrial consultant, and his problem-solving skills were called upon by many of the leading turbine manufacturers in Europe and elsewhere. Indeed, the presence of his turbine engineering group in Zurich was an important contributory factor in the establishment of Switzerland as a major manufacturer of equipment in this field. Those interested in further details of Stodola's turbine work should consult ref. 10, written by one of his former students, or his own English publications which appeared in *Engineering* and the *Sulzer Technical Review*. Bibliographies can be found together with other information in refs 11 (to 1929) and 12 (1930 onwards).

Stodola was granted many academic and professional honours, including the ASME 15th Anniversary Medal in 1930, and the Institute of Mechanical Engineers James Watt International Medal in 1941. Given the date of the latter, the award of the medal to a German-speaking Central European must have had particular significance; the closing paragraphs of the letter [13] informing Stodola of the award are worth quoting as a masterpiece of British understatement, avoiding any reference to the distasteful hostilities:

> The Medal is usually struck in gold, but in view of certain restrictions at present obtaining in this country the medal will be struck in silver gilt, and the Council therefore decided that you be asked to accept an additional presentation to the value of £20 to be in any form chosen by yourself.
>
> As it is probable that you will be unable to come to this country to receive the Medal personally, it is proposed to ask His Excellency the Swiss Minister in London to receive the medal on your behalf.

An engineer's philosophy

After his retirement in 1929 Stodola continued to work and publish. His most interesting publication of this period is a short book entitled *Thoughts on the Philosophy of an Engineer*,[14] first published in 1931. In this he combined his thoughts on the role of the engineer in society with a detailed presentation for the non-specialist of the new physics.

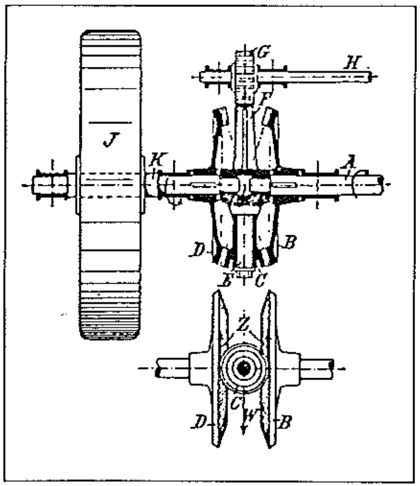


Fig 4 Inertia governor. Inertia of flywheel J *is utilised to sense any acceleration of Shaft* A *and transform it ultimately into movement of control member* H

The engineer and society

The first two chapters of *Philosophy of an Engineer* are based on addresses given by Stodola in 1929 and 1926 respectively to the student body at the Swiss Federal Institute of Technology. In many ways both chapters have a surprisingly modern ring, and many of the problems mentioned continue to tax the engineering profession today. In the first chapter, for example, Stodola looks at the rather uneasy relationship between industry and the academic engineer, and at the rival claims of theory and empiricism. Even in the 1920s, European industry was often unhappy with the abilities of engineering undergraduates: Stodola quotes an industrialist who boasts that his company is successful precisely because it refuses to employ university graduates! Of course, many of the important technological advances of the previous decades in electrical and mechanical engineering had indeed been made by gifted inventors with little or no theoretical knowledge, and the temptation to denigrate academic learning was ever-present. Stodola, while admitting the many discoveries made intuitively, is at pains to point out the dangers of over-reliance on such an approach. He calls for greater give-and-take on both sides, recognising that advanced subject knowledge is not the only requirement of a university graduate. He states his main conclusions forcibly in ref. 14, pp 9–10:

> 1. Important sectors of industry must recognise more clearly that the empirical approach, which they still hold so dear, is often a very expensive approach, and offers no guarantee of a satisfactory outcome. Only when combined with research and a scientific, critical outlook can lasting success be achieved. More than anything [. . .] it is a question of according to science a higher place on the scale of national values.
>
> 2. The rivalry of the 'practical man' and the academic engineer must be resisted, and replaced by a feeling of solidarity. Neither a technical education nor a university degree guarantees in itself competence for a responsible position (in industry): the important thing is the whole personality [. . .] Recent graduates are often still overwhelmed by the deeper intellectual experience which only the university can offer, and they may well need to be shown patience and consideration at the start of their practical career. [. . .] For their part, however, graduates must also appreciate the difficulties of industry, and behave calmly and with good sense even in trying circumstances.
>
> 3. While it is the duty of state and society

> to attend properly to the adequate education of the average majority, it is in the general interest to support to a significantly greater extent the development of the talented few, since it is the latter who will ensure higher technological and human progress. A longer period of study for such students is to be strongly recommended, thus allowing time not only for their intellect to mature, but also for their developing ethical and spiritual forces to lead to a clarification of their philosophy of life.

Plenty to think about there, even in the late 1980s, and even if some of it may sound elitist and idealistic to modern ears!

In the second chapter of *Philosophy of an Engineer*, Stodola turns to an even more intractable problem, that of the general role of the engineer in society. In particular he defends the engineer against accusations of responsibility for the perceived ills of technology, the greatest of which in 1930 was mass unemployment. He accurately describes the automated factory of the future: "full of humming machinery yet empty of workers. At one end trains arrive with raw materials, which are automatically unloaded; at the other, yet more machines load and despatch the products. Only a few, highly qualified, specialist workers are needed." In common with many of the science fiction writers and film makers of the time Stodola raises the spectre of a divided society, in which an underclass of unemployed suffers misery and degradation, while an elite enjoys the fruits of technological development. Is the engineeer therefore guilty for having rendered such things possible?

Stodola's defence of the engineer is at first traditional, if somewhat simplistic (ref. 14 p. 17):

> Suppose that a workman leaves a hammer lying about a house. During the night, a burglar is disturbed, seizes the hammer, and uses it as a murder weapon. Is the workman then responsible for the tragic outcome? Even if we feel that anyone who uses dangerous tools should be doubly aware of the consequences of carelessness, and consider the workman guilty of negligence, we should certainly not hold him responsible for the murder itself. Similarly, we engineers must protest vigorously if we are accused of responsibility for the lingering deaths of so many children at the beginning of last century, as a result of the unrestrained misuse of child labour in the English textile industry.

Yet Stodola certainly does not allow the engineer the liberty to retreat into a value-free world of the intellect, tempting though this may often be. Engineers, as citizens, have a responsibility to take part fully in the public, intellectual and cultural life of the community. Indeed, because of their specialist abilities, they have a particular duty to do so; Stodola has only scorn for those seduced by the 'magic' of technology to the exclusion of everything else, or for 'patent hunters' who abnegate their responsibilities in the pursuit of fame or wealth. Furthermore, engineers all too often neglect human factors in their work; cooperation between the various elements of society is what is needed if progress is to be made and undesirable effects avoided (ref. 14, p. 24):

> The engineer works not only with metal, but also with human materials, all of whose strengths and weaknesses he must understand; he is above all the mediator between Capital and Labour, and therein lies part of the tragedy of his profession.

Wrestling with the new physics

The remainder of *Philosophy of an Engineer* is very different from these first two chapters, being devoted primarily to an exposition of recent developments in the natural sciences – notably relativity and quantum theory. (Remember how very new these developments were in 1930. Einstein's views on the quantised nature of radiation were not widely accepted until the early 1920s; the uncertainty principle was as recent as 1927). By the time he retired, Stodola had been interested in the new physics for many years. At a colloquium in 1980 attended by a number of distinguished former students, Claude Seippel recalled this period[15]:

> The atmosphere in the large work room was relaxed. Stodola, returning from the lecture theatre or the drawing office, willingly shared his most recent thoughts and ideas. Conversation often ranged over the material he was later (this was 1923) to put into his *Philosophy of an Engineer.* Physics, for example. The new quantum theory made him uneasy. "How, and in what time, does an electron move from one orbit into another? How does the observed frequency arise?" Quantum theory was not to be understood, one must simply believe in it! Stodola's misgivings were to his credit. He was not the only one – Einstein too had qualms.

Stodola seems to have spent the summer of 1930 working on those sections of *Philosophy of an Engineer* dealing with the new physics. Like many engineers (and others) then and since, he had great difficulties coming to terms with some of the ideas. Unlike most novices, though, he moved in an academic circle which included many of the originators of the new theories, and he was able to turn to them directly for clarification. (Einstein, for example, had even been a colleague of Stodola, teaching at the Swiss Federal Institute of Technology in Zurich for a short time.) Two interesting letters to Einstein survive from this period. On 13 July Stodola wrote to say that he had finally found time for a long-postponed serious study of relativity, but that there were certain things he still could not follow (Figure 5). There follows an extensive query concerning relativity and 'cosmic' time, but it is in the closing paragraph of the letter[16] that one feels most for Stodola:

> I have also asked Professors Weyl and Pauli, but these gentlemen have their heads so full of other matters, and express themselves so abstractly, that in my desperation I saw no salvation except to turn to the master of masters.

The master's reply does not survive, but he must have responded immediately, since by 18 July Stodola was writing again, thanking Einstein for his help, but adding another four sides of technical questions!

Stodola ultimately gave a very creditable outline of relativity and quantum theory, although his reservations about the latter remained, especially in so far as the uncertainty principle appeared to offend against causality. Indeed, he expressed these reservations in print (ref. 14, p. 65):

> The strict law of causality is replaced by the concept of probability, and in an incomparably more radical way than was the case a few decades ago with the kinetic theory of gases. In the latter, colliding molecules interact according to precisely determined laws, even if the details of these laws are not known exactly. Only the enormous numbers of molecules, and the impossibility of observing them all individually, [. . .] leads to the random distribution of positions, velocities and directions [. . .]
>
> Things are completely different in the new physics, however, in so far as subatomic processes within the "cloud of probability" are concerned. [. . .] Before an observation, the very existence of an electron is shrouded in darkness. Only the statistical probability of its being found in a certain region is known; whether or not it actually appears is a matter of pure chance. [. . .] The hitherto universally recognised law of causality is for ever destroyed, and with it disappears a part of our view of the world (*Weltanschauung*), a belief in which was an inner compulsion and a deep reassurance.

Stodola's *Philosophy of an Engineer* was favourably received, and Springer in Berlin published three editions in two years. (After 1933, of course, expositions of such 'Jewish' physics could not be tolerated in Germany, although abridged versions of the book appeared again in Switzerland in 1937 and 1940.) Following its first appearance, Stodola received an encouraging letter from Max Planck, taking issue, however, on the matter of causality. This letter and Stodola's reply are worth quoting in their entirety. They testify both to Stodola's intellectual stature and to his modest nature, and form a fitting conclusion to this article:

> Berlin, 2.12.31
> Esteemed Colleague
>
> Having read your 'philosophical

thoughts', which you very kindly sent me, I am moved to express again, and more forcibly, my sincere thanks; also to say how stimulating and rewarding I found your clear and elegant exposition. What makes it so effective and gripping is that you address not only the analytical side of the human intellect, but the whole person. You know already that I agree entirely with you on the main points. Only on one single – although important – matter are our views in conflict, and this is also a reason for my writing to you now. You use the Heisenberg uncertainty principle as an argument against the acceptance of a strict causality, whereas I take the view that to ask for simultaneous exact values of position and momentum is a question with absolutely no physical meaning, and the impossibility of giving a decisive answer to a meaningless question should not be taken as a failing in the law of causality. This is just a very brief expression of my view. I shall be giving a lecture on 28 January here at the *Akademie*, and on 23 February in Lübeck, on the concept of causality in physics, and shall certainly take the liberty of sending you the printed version. There I hope to justify my ideas more fully.

Sincerely and respectfully yours,
M Planck

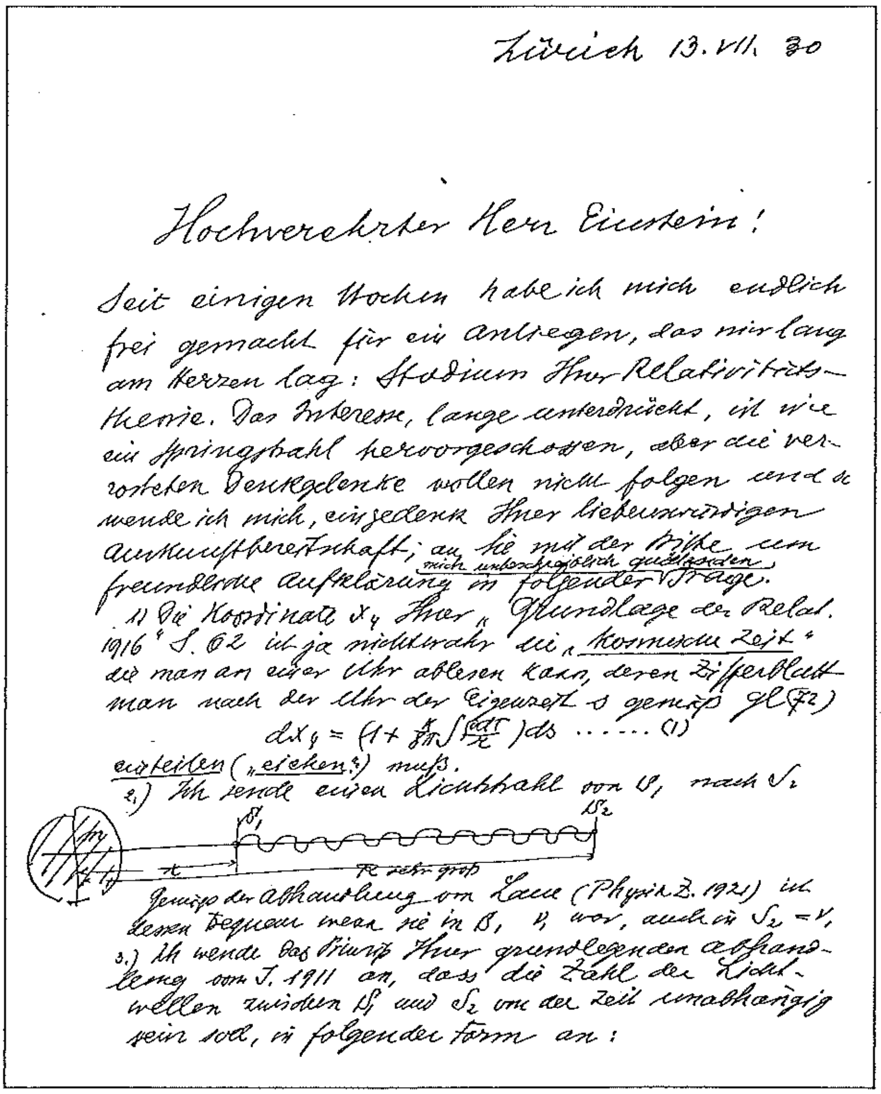
Zurich, 7.12.31
Esteemed *Geheimrat*‡

Nothing could give me more pleasure and do me greater honour than your enormously stimulating letter. My book was certainly very favorably received by the *Verein Deutscher Ingenieure*, but is by its very nature known only in the engineering and technical circles for which it is intended. That you, however, the highly regarded pioneer and originator of these great transformations [in physics] . . ., should be so kind as to examine my little book in such detail, is to me a great honour and satisfaction.

I took a risk, of course, in wishing to enter the realms of theoretical physics and express my own, even critical, opinions. Your kind clarification of the Heisenberg uncertainty principle shows me the danger to which an outsider is exposed, and has caused me to reconsider how I came to my conclusions.

I consider now very naive my deep belief in the ultimate strict causality of the physical world; but I cannot answer the difficult question whether and how science will ever verify such a law. As I understand Heisenberg's theory, it will always be impossible to carry out the necessary precise measurements for events on an atomic scale. Should we expect, nevertheless, to be able to carry out a sufficiently approximate confirmation? How close must such approximations be to satisfy us? Which of my premises is false? I am completely in the dark, and look forward with eagerness to receiving the printed text of the lectures you mentioned, for which I thank you greatly in advance.

Most sincerely yours
A Stodola[17]



Zürich 13.VII. 30

Hochverehrter Herr Einstein!

Seit einigen Wochen habe ich mich endlich frei gemacht für ein Anliegen, das mir lang am Herzen lag: Studium Ihrer Relativitäts-theorie. Das Interesse, lange unterdrückt, ist wie ein Springstrahl hervorgeschossen, aber die verrosteten Denkgelenke wollen nicht folgen und so wende ich mich, eingedenk Ihrer liebenswürdigen Auskunftbereitschaft, an Sie mit der Bitte um freundliche Aufklärung in folgender mich unbezwinglich quälenden Frage.

1) Die Koordinate x_4 Ihrer „Grundlage der Relat. 1916" S. 62 ist ja nichtwahr die „kosmische Zeit", die man an einer Uhr ablesen kann, deren Zifferblatt man nach der Uhr der Eigenzeit s gemäß Gl(72)

$$dx_4 = \left(1 + \frac{\kappa}{8\pi}\int \frac{d\tau}{r}\right) ds \quad \ldots\ldots (1)$$

einteilen („eichen") muß.

2.) Ich sende einen Lichtstrahl von S_1 nach S_2

Gemäß der Abhandlung von Laue (Physik. Z. 1921) ist dessen Frequenz, wenn sie in S_1 ν_1 war, auch in $S_2 = \nu_1$

3.) Ich wende das Prinzip Ihrer grundlegenden Abhandlung vom J. 1911 an, dass die Zahl der Lichtwellen zwischen S_1 und S_2 von der Zeit unabhängig sein soll, in folgender Form an:

Fig 5 Letter from Stodola to Einstein, raising number of technical points concerning theory of special relativity

Conclusion

My initial aim in preparing this article was simply to present the control engineering work of Aurel Stodola to a wider audience, and I hope to have done this, albeit briefly, in the first few sections (further details can be found in ref. 3). In researching Stodola's contribution to control, however, I began to feel that a description of some of his other achievements would be of equal interest to control engineers; in particular, I found his *Philosophy of an Engineer* especially thought-provoking. What is so striking about the book is not so much Stodola's detailed personal philosophy, which is naturally deeply rooted in his own time and background. It is rather the seriousness with which he views the engineering profession, its responsibilities and its relationship with pure science: seen in this light there is much of relevance to us today. And finally, of course, a fascinating picture emerges of an engineer not simply coming to terms with the weighty problems of wave-particle duality, quantum theory and relativity, but publishing a clear exposition for non-physicists! Which of us today would dare to attempt a similar book on superstrings and grand unification?

Acknowledgements

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**This subsection is based primarily on parts of ref. 3.*

†The inertia-only governor (no proportional action) was invented by the Siemens brothers in 1845. The device, of course, had the disadvantages to be expected from what was basically a derivative-only controller, and it was not until it was combined with a conventional centrifugal governor that it became practicable, coming into widespread industrial use by the 1890s.

‡Literally 'privy counsellor', but an honorary title often awarded to distinguished academics.