Life–Cycle Cost Multidisciplinary Optimization for Prandtl–Plane

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Summary

The paper deals with multi-disciplinary optimization of an innovative aircraft configuration, with an objective function expressed in terms of life–cycle costs. The algorithms utilized to model the mechanical behavior are necessarily first–principles based if the configuration is innovative. On the other hand, the algorithm used for the life–cycle costs is necessarily based upon statistical data available in the literature. The algorithm for the life–cycle costs of traditional configurations is properly adapted to innovative ones, through a procedure outlined in the paper. This results in a life–cycle cost that is a linear function of empty weight and useful fuel weight. This allows one to separate the optimization process from the economic analysis. Specifically, one may perform a parametric optimization, with the objective function given a linear combination of these two quantities; the value of the weights to be used is obtained – in a completely independent way – from the life–cycle cost analysis. The procedure is illustrated through a numerical application to the design of the wing system of a Prandtl-Plane, which is an innovative box–wing configuration with the distinguishing feature of a considerably reduced induced drag.

Introduction

The air transportation market growth has led to the design of some highly innovative New Large Aircraft (NLA), for which cost prediction cannot be obtained using the statistical data, because these are available only for traditional aircraft configurations. Since costs are becoming more and more important in determining the success of a new aircraft an optimization process that takes in account life–cycle costs is paramount. Thus, the motivation for this paper is to introduce life–cycle cost considerations in choosing the objective function for an existing methodology for MDO/CD (Multi–Disciplinary Optimization for Conceptual Design) of innovative airplane configurations, thereby extending the formulation of Ref. [1], which the reader is assumed to be familiar with. The ultimate objective of the work is to obtain a preliminary estimate of the costs of an innovative configuration which would allow the manufacturer to know whether the project is convenient or not. In this paper, however, we have more limited objectives, *i.e.*, to develop a procedure for MDO/CD for innovative configurations and to illustrate it through a numerical application to the design of the wing system of a specific airplane: a highly innovative box–wing configuration, known as the Prandtl–plane, [2], which has, as a distinguishing feature, a considerable reduction of the induced drag.

Specifically, we started with a life–cycle cost model for traditional configurations (from Ref. [3]), which is based upon statistical data available in literature. Then, we extended it to innovative civil–aircraft configurations, by using a procedure based on the assumption that the cost per pound for each part for traditional and innovative configurations are equal (in the implementation, these costs have been obtained using data available for the Airbus A380). Finally, we used it within an MDO–CD context, in order to show how the designer may include financial considerations during the conceptual design stage. In the process, we show that the optimization process may be decoupled from the economic analysis. Specifically, one may start from the observation that the resulting algorithm for the Total Aircraft Life–

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cycle Cost, $TALC$, is a linear function of empty weight W_E and useful fuel weight W_F, as

$$TALC = C_0 + C_E W_E + C_F W_F \tag{1}$$

where C_0 is the portion of the cost that is independently of W_E and W_F, whereas C_E and C_F are the cost increases per unit W_E and W_F, respectively.

Thus, one may perform the optimization process completely independently from the economic analysis. Specifically, one may perform a parametric optimization, with the objective function given as

$$J = \eta_E \frac{W_E}{W_{E_{Ref}}} + \eta_F \frac{W_F}{W_{F_{Ref}}} \tag{2}$$

(Ref denotes a reference value), with $\eta_E = 1 - \eta_F$ used as a parameter (note that the constant part of the cost, C_0, is inessential in the optimization).

The value of η_E is obtained by comparing Eq. 1 with Eq. 2. Thus, the two processes may be performed in a completely independent way. This is a considerable advantage because the optimization process is computer intensive, whereas the estimate of life–cycle costs is computer efficient but requires the use of predictions of statistical distributions of parameters (such as the cost of fuel), which may change from day to day, depending upon the market conditions.

The paper is structured as follows: first, we present a review of the costs that are included in the analysis. Then, the procedure is is illustrated by applying it to the Prandtl–Plane, which, as mentioned above, is an innovative box–wing configuration with the distinguishing feature of a considerable reduction of the induced drag. - specifically, this is a biplane with a backward–swept lower front wing and forward–swept upper back wing connected to each other by vertical surfaces. Finally, a procedure to adapt the costs for the traditional configuration to those for an innovative one is presented in Appendix A; this requires an estimate of the manufacturer's costs, which are discussed in Appendix B.

It is worth noting that the algorithms used for modeling aerodynamics, structures, and aeroelasticity are those developed in the past by the authors and their collaborators: the stress analysis is based on finite elements for beams, the structural dynamics is based upon natural modes, for the aerodynamic analysis a boundary–element quasi–potential–flow method is used. For the sake of conciseness, for the details of the model used are not presented here and the reader is referred to Ref. [1].

Total Aircraft Life Cost

To begin with, one must choose the type of cost to be optimized. One could chose the profit of the manufacturer. However, a new aircraft program should take into account along with the maximization of its own profits also the requirements (and the profit) of the costumer (*i.e.*, airline), since these are crucial to the sale – no sale, no profit. This tread–off involves a lot of financial considerations that are more the domain of the economist than of the engineer. As engineers, we have chosen to minimize the aircraft life–cycle costs to the airline, which is a relatively well defined function of the design parameter (see Ref. [3]. This includes both, acquisition and operating costs. Using the terminology (and symbols) of

Ref. [3], we identify the objective function J with the Total Aircraft Life–cycle Cost. This is given by

$$TALC = AEP + C_{oper} \tag{3}$$

where AEP denotes the Aircraft Estimated Price and C_{oper} the operating costs for one aircraft corresponding to a commercial life of N_y years (in the applications, we used $N_y = 20$). These two types of costs are addressed in the following two subsections, only to indicate the level of details that has been considered. For the specific expressions used, the reader is referred to Ref. [3].

Aircraft Estimated Price

The Airplane Estimated Price is influenced by the non–recurring costs C_{RDTE} (where $RDTE$ denotes Research, Development, Test, and Evaluation), by the average recurring costs C_{man} (manufacturing costs per airplane, *i.e.*, the cost to build N_m airplanes divided by N_m), and by the desired manufacturer's profit, C_{pro_m}. Of course, profits can change significantly with market conditions; here we assumed as given. [Moreover, it may be observed that the manufacturing costs per airplane have a strong reduction as the number of airplanes produced increases. This is due to the “learning curve effect", which expresses mathematically the reduction in man–hours required to build each airplane because of workers' experience and improved capability. The Airplane Estimated Price represents the average price of all the airplanes produced, assuming to sell them with the same price over the entire airplane program. Therefore, during the entire program length, production costs of each airplane will be higher than the price at which each airplane is sold and the manufacturer will start to have a profit only when the inversion of the ratio between costs and price is realized.]

In any event, starting from the knowledge of an estimate of the costs per pound for each part of an airplane, it is possible to determine the Airplane Estimated Price as follows:

$$AEP = (1+F_{pro_R})\sum_{i=1}^{N} CPP_{RDTE_i} W_i + (1+F_{pro_M})\sum_{i=1}^{N} CPP_{man_i} W_i + (1+F_{pro_A}) CCP_{assembly} W_E \tag{4}$$

where: N denotes the number of parts of an airplane (*e.g.*, wing, horizontal tail, vertical tail, fuselage, landing gear, engines, and system & payloads); W_i the weight of the ith part; CPP_{RDTE_i} the cost per pound of the ith part for the $RDTE$ non–recurring phases; CPP_{man_i} the aircraft average cost per pound of the ith part for the manufacturing phase. The last term (final assembly) is still part of the manufacturing costs; the corresponding cost per pound is relative to the empty weight W_E. Finally, F_{pro_R}, F_{pro_M}, and F_{pro_A} are the profits for $RDTE$, manufacturing, and assembly phases, respectively.

The procedure to estimate the costs per pound for an innovative configuration starting from a traditional configuration is addressed in Appendix A. This in turn, requires an estimate of the price, which is considered in Appendix B.

Operating Cost

A method for estimating the operating costs of commercial airplanes (*i.e.*, the costs incurred by the airline for operating one airplane during its life time) is outlined in this section. This cost is typically broken down into two components, *DOC* and *IOC* (Direct and Indirect Operating Costs, respectively, Ref. [3]).

The direct operating costs are broken down into components such as: (1) the direct operating cost of flying, which consists of the crew cost, the fuel and oil cost (which depends on mission fuel, oil and lubricants consumption per year of service and on their prices), and (2) the direct operating costs of maintenance, which includes costs associated with labor and spare parts, for for airframe and engines. Of course there are other costs that do not affect the optimization process (see term C_0 in Eq. 1). These include: the costs of depreciation, which deals with the airplane loss of value with time including airframe, engines, avionics system and spare parts; landing and navigation fees (which are important in the optimization process when noise is taken into account) and registry taxes; the direct operating cost of financing, which depends on how an airline is financing his fleet of airplanes, in particular whether it needs to borrow money or it is able to use its own money.

The Indirect Operating Costs vary significantly from one operator to another, depending upon the different strategies used. They include costs for: passenger services; maintaining and depreciating ground equipment and ground facilities (building, lighting, heating and administrative costs); the cost for promotion, sales and entertainment; the cost for general administrative expenses. These affect the optimization results, because, following Ref. [3], they are assessed as a fixed percentage of the direct costs, thereby altering the balance between the aircraft estimated price and the operating costs.

MDO for Prandtl–Plane

In order to illustrate the procedure, we addressed the conceptual design of the Prandtl–Plane. As mentioned above, the modeling for the airplane mechanics is given in Ref. [1] and is not repeated here. The multidisciplinary design optimization process (see Ref. [4] uses the Broyden Fletcher Goldfarb Shanno method (see Ref. [5]), with quadratic extended interior penalty function (see Ref. [6]).

The characteristics of the Prandtl–Plane are similar to those of a typical modern large long–range transport jet aircraft; specifically, we chose those of the $A380$ category, with 622 passengers payload, an assumed cruise altitude of 30.000 ft, a cruise Mach Number of $M_\infty = 0.75$. We considered for the optimization process only the wing system, with a wing span set at 230 ft, with a prescribed fuselage (239 ft long, 27 ft wide, and 23 ft deep), and a prescribed propulsion system (four underwing–mounted turbo–fan engines). The cost per pound utilized as inputs of a multi–disciplinary optimization process (see Appendix B) are obtained from the $A380$.

For the optimization process shown below, we assumed a fixed range, $R = 6,000$ nm. The objective function for the optimization is (the difference with respect to Eq. 2 is only due to the fact that in this application were are dealing with the design of the wing only)

$$J = \eta_W \frac{W_W}{W_{E_{Ref}}} + \eta_F \frac{W_F}{W_{F_{Ref}}} \qquad (5)$$

where we used $W_{E_{Ref}} = 100$ metric tons and $W_{E_{Ref}} = 150$ metric tons (these values are introduced only

Design parameters / objectives	$\eta_W = 0.5$	$\eta_W = 0.6$
Wing/tail half–span (m)	33.37	32.61
Wing root chord (m)	11.00	10.95
Wing tip chord (m)	7.46	7.51
Tail root chord (m)	10.60	10.52
Tail tip chord (m)	6.31	6.27
Wing root built–in angle (degree)	5.01	4.96
Wing tip built–in angle (degree)	3.64	3.66
Tail root built–in angle (degree)	4.63	4.67
Tail tip built–in angle (degree)	3.67	3.66
Wing sweep angle (degree)	29.17	28.78
Tail sweep angle (degree)	-33.23	-33.12
Empty weight (ton)	143.96	143.61
Useful fuel weight (ton)	161.37	161.63

Table 1: Optimal design parameters for Prandtl–Plane configuration

as scaling factors, so as to make J of order one, a requirement dictated by the fact that we are using the penalty function method to impose the constraints). The results of the optimization (*i.e.*, optimal design parameters, as well as wing weight and useful fuel weight) are presented in Table 1 for η_W =0.5 and 0.6. [Notice that the variation of the parameters is relatively small. Thus, in this case, two values of η_E are adequate for our objectives (as long as the value of η_E is close to the range under consideration – and, indeed, it is, as shown below).]

Next, consider the cost analysis. Figures 1 and 2 show the $TALC$ as a function of the wing weight W_W and of the useful fuel W_F, respectively. It is apparent that $TALC$ grows linearly with W_W and W_F (of course, this can be seen also by examining the lengthy sequence of equations used to obtain the figures, see Ref. [3]). Thus (the difference with respect to Eq. 1 is only due to the fact that in this application were are dealing only with the design of the wing),

$$TALC = C_0 + C_W W_W + C_F W_F \tag{6}$$

where C_0 is the portion of the cost that is independently of W_W and W_F, whereas $C_W = 7,650\$/kg$ and $C_F = 4,100\$/kg$ are the cost increases per unit W_E and W_F, respectively. Correspondingly, we have $\eta_E = 0.445$. The corresponding geometry, obtained by linear interpolation, is presented in Figs. 3 and 4.

Conclusions

A procedure to perform a multi–disciplinary optimization for innovative configurations based on life–cycle costs has been presented. This includes a procedure to adapt to innovative configurations the algorithm for the cost estimate of traditional configurations. In addition, it was shown how the optimization process (which is computer intensive, but robust) may be decoupled from the cost analysis (which is inexpensive, but subject to uncertainties which evolve with time, as they depend upon the market conditions). Applications to the Prandtl-Plane have been presented.

Reference

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A. Cost breakdown

As mentioned in the main body of the paper, the optimization procedure requires an estimate of the cost per pound of each aircraft component. The procedure used to accomplish this – the key point that allows us to extend the formulation from a traditional configuration to an innovative one – is based upon the knowledge of typical cost breakdown for traditional airplane and on a proper weight breakdown estimate. From these, one obtains the cost per pound for each component – this is then assumed to apply to innovative configurations as well.

Typical cost breakdown by parts of commercial aircraft is given by industry sources, both for non–recurring and recurring costs, whereas the fractional weight breakdown of commercial aircraft may be easily obtained from statistical data available in the literature. Dividing the cost per part by the corresponding weight for each part determines the cost per part per pound (all the data are relative to the A380, which has specifications similar to those being considered in this paper for the Prandtl-Plane).

Consider first the non–recurring costs, that is, costs for $RDTE$ (Research, Development, Test, and Evaluation). Applying the typical cost breakdown yields the airplane cost per part shown in Table 2. [This was obtained as follows: the cost percentages are based on data available in the literature, see for instance Ref. [7]; the weights are based upon data available in the Internet, in particular on the Airbus web-site; the total cost is estimated with the procedure outlined in Appendix B which yields a cost estimate of 11.69 B$ (this result is in excellent agreement with the value of 11.5 B$, available in Ref. [8]).]

Next, consider the recurring costs (*i.e.*, manufacturing costs C_{man}). These costs deal with total manufacturing and development costs that the manufacturer has to cover during the program to produce the entire fleet. Dividing the total manufacturing cost by the number of aircraft produced yields to the Average Aircraft Cost, *AAC*. As for the non–recurring costs, the typical cost breakdown corresponding to

Parts	Cost (%)	Cost per part (B$)	Weight (lb)	Cost per pound ($/lb)
Wing	20	2.34	131,936	17,735
Horizontal Tails	5	0.58	16,544	35,357
Vertical Tail	4	0.46	7,760	60,303
Fuselage	37	4.32	136,603	31,688
Landing Gear	1	0.11	30,583	3,825
Engines	8	0.93	104,320	8,972
System & Payloads	25	2.92	182,985	15,984
Total	100	11.69	610,733	

Table 2: Non–recurring costs per part per pound

Parts	Cost (%)	Cost per part (M$)	Weight (lb)	Cost per pound ($/lb)
Wing	27	53.6	131,936	406.4
Horizontal Tails	6	11.9	16,544	720.2
Vertical Tail	4	7.9	7,760	1023.6
Fuselage	28	55.6	136,603	407.0
Landing Gear	3	5.9	30,583	194.8
Engines	9	17.9	104,320	171.3
System & Payloads	17	33.8	182,985	184.5
Final Assembly	6	11.9	610,733	19.5
Total	100	198.6	610,733	

Table 3: AMC costs per part

the manufacturing phase is used to find the cost per part. Dividing the cost per part by the corresponding A380 related weight for each part determines the cost per part per pound. Starting from *AAC*, equal to 198.6 M$ (see Appendix B), we obtain the costs per part and the corresponding costs per pound of Table 3.

B. Estimate of RDTE and manufacturing costs

As mentioned in Appendix A, in order to obtain the costs per part per pound, it is necessary to have an estimate of the total manufacturer's costs, both non–recurring and recurring.

Here, we outline a procedure for the preliminary costs estimate for new aircraft during the conceptual design phase. This analysis allows one to evaluate the amount of resources needed to build a new aircraft and gives an essential effort to a proper program decision making. Two different kinds of costs appear during an aircraft manufacturing program. The first one encompasses all the non–recurring costs and the second includes recurring costs and consists of manufacturing costs associated with the production of each aircraft. Finally it is important to underline that life–cycle costs is obtained by cost evaluation of the activities, as functions of technical parameters (cruise speed, payload, take–off weight, fuel consumption, etc.). The cost incurred during the first few years of an aircraft project is represented by the four different basic $RDTE$ phases. The $RDTE$ cost is non–recurring and is accumulated during activities such as design, construction, ground and flight airplanes testing. It includes several components (see again Ref. [3]), such as the costs for: airframe engineering and design, engines and avionics, labor, material and tools to manufacture the flight test airplanes, quality control, flight test operations, test and simulation facilities, $RDTE$ profit, and finance of the $RDTE$ phases.

The costs model illustrated in this section has been applied to an aircraft having the technical parameters of an Airbus A380. Specifically, we considered a four mounted engines aircraft, with a takeoff thrust of 91,300 lb, a takeoff weight of 1,234,580 lb and a cruise speed of 495 Knts. The calculations for the $RDTE$ costs, assuming that five test airplanes are built for both static and flight tests, with a profit of 10%, a test and simulation cost as a fraction of 20% of the total RDTE cost, a suggested financing costs of 10%, led to the C_{RDTE} estimate of 11.69 B$.

Next, consider recurring costs. As for the non–recurring calculations, the recurring manufacturing costs are evaluated by considering several processes characteristic of this phase. The model used allows one to estimate the total manufacturing cost, that is the cost incurred to build N_m aircraft produced during the entire program. The aircraft are assumed to be manufactured at once with the same time money value, without considering variations over many calendar years. Manufacturing costs are broken down into several cost categories (see Ref. [3]) such as total airframe engineering and design cost for the entire program, airplane program production cost, cost of engine and avionics as acquired from vendors, cost of interior, labor cost to manufacture N_m airplanes to production standards, manufacturing material cost incurred while manufacturing N_m airplanes, tooling cost to produce N_m airplanes, quality control cost associated with building N_m airplanes, production flight test operations cost, and the cost to finance the manufacturing phase.

All the costs are estimated with the same–time money value used to evaluate the complete manufacturing costs necessary to produce N_m airplanes. These assumptions in costs estimate lead one to the Airplane Estimated Price AEP, which represents the average price, based on costs, of each airplane produced.

It is necessary to underline that the manufacturing costs and the corresponding AEP are strongly affected by the number N_m of airplanes manufactured (here set at 1,000, see Ref. [8]). In particular, the difference between the AEP and the real Airplane Market Price AMP available from literature (equal to 250M\$, see again Ref. [8]) is not negligible. We have assumed the estimate of the $RDTE$ costs, independent from the number of airplane manufactured, to be a good approximation. The manufacturing costs can be evaluated from $C_{man} = (AMP\ N_m - C_{RDTE})/(1+F_{pro_m})$ with a desired profit of $F_{pro_m} = 20\%$, which is reasonable in the case of the A380, because of the position of monopoly that Airbus will have in the very large aircraft market, and where AMP in place of AEP allows us to determine a more reasonable value for the manufacturing cost related to the A380 program of 184.1 B$.

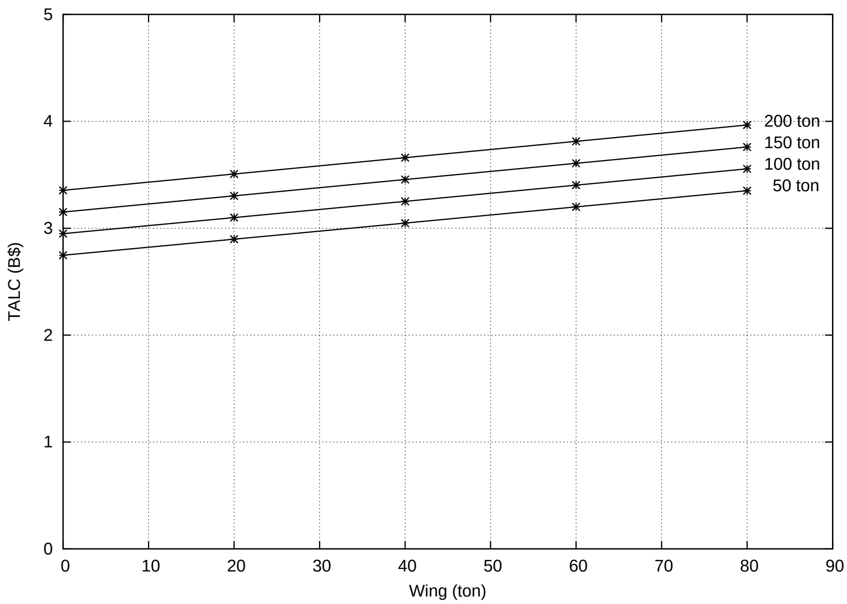

Figure 1: TALC as a function of W_{wing}, for $W_{fuel} = 50, 100, 150, 200\ ton$.

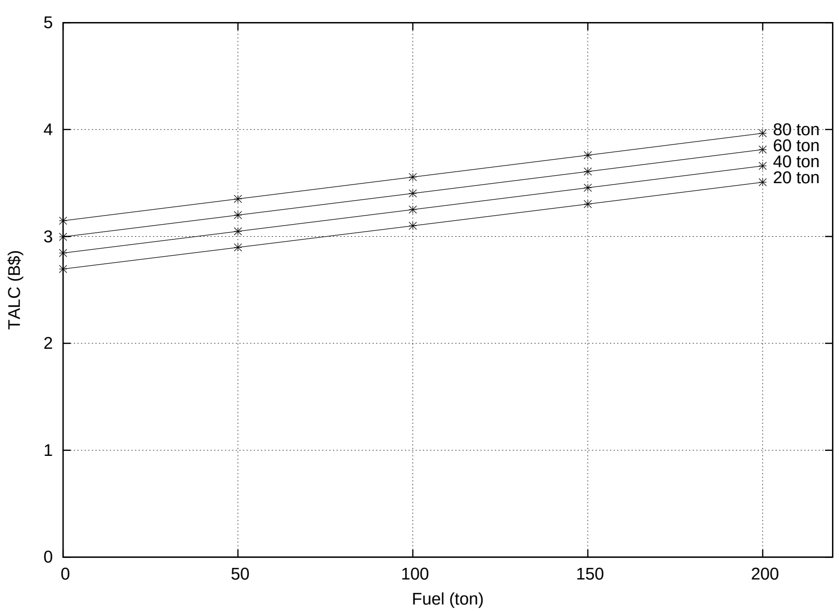

Figure 2: TALC as a function of W_{fuel}, for $W_{wing} = 20, 40, 60, 80\ ton$.

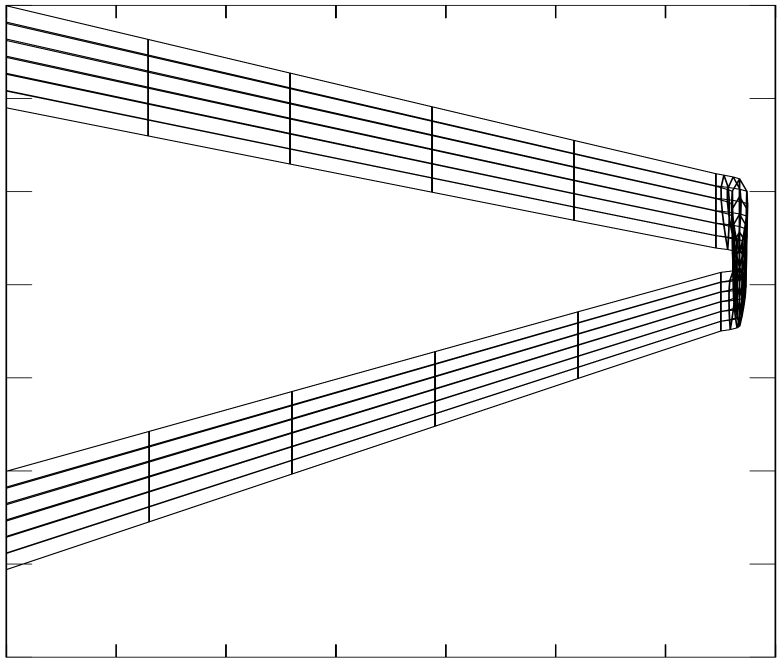

Figure 3: Prandtl–plane: top view

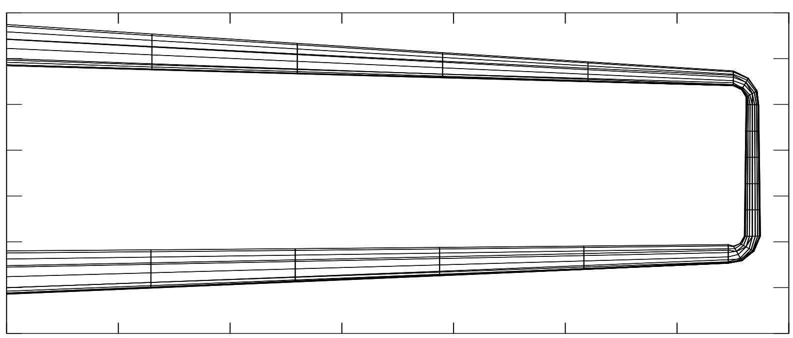

Figure 4: Prandtl–plane: front view