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THE PRINCIPLE OF HARMONIC COMPLEMENTARITY IN EVALUATION OF A SPECIFIC THRUST JET ENGINE

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The fundamental idea of this paper is to calculate the specific thrust force of a propulsion system (thrust) [1], class of air-jets engine, with application to turbojet simple flow, based on the definition and use of harmonic complementary patterns between gas dynamics functions of impulse and thrust.

Keywords: thrust force, complementarity, harmony, turbo engine

1. Introduction

In the following shall be considered a schematic diagram [2] of a generalized nozzle, as in Fig. 1

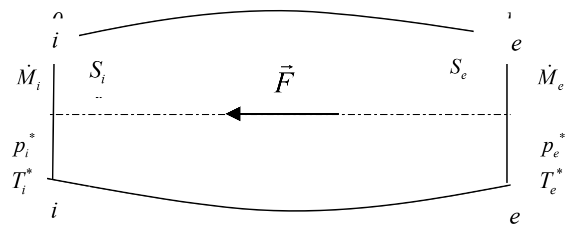

Fig. 1 Schematic diagram of a generalized nozzle

where the characteristic parameters nature such as

- mass flow, $\dot{M}$;
- p^*, T^*, total pressure and temperature;
- geometric area , S ,

define the two states of the fluid, corresponding to the

- entry to the nozzle, index *i*;
- exhaust from the nozzle, index *e*.

Of course, the force developed by the nozzle, forward $\vec{F}$, consists of

- thrust elements, $\vec{T}_j$;
- propulsion elements, $\vec{P}_k$;

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- compound elements, thrust-propulsion $\vec{C}_l$.

As a result, the summed force becomes [3]

$$\vec{F} = \sum_{j=1}^{n} \vec{T}_j + \sum_{k=1}^{m} \vec{P}_k + \sum_{l=1}^{p} \vec{C}_l \tag{1}$$

In principle, foundations of the physical and analytical holistic model (global) evaluation of force performed by a generalized nozzle, F_i, which can be represented by any of the components of jet engine, inlet device, compressors (centrifugal and aerodynamic), combustion chamber, turbine, exhaust system of the turbine and jet nozzle gas, all passed through a working fluid.

2. Mathematical basics of a holistic model

In general [4], the amount of force developed by the nozzle, F_i, can be expressed by the formula [5]

$$F_i = F_{ce} - F_{ci}, \tag{2}$$

F_c symbolizes the current local force, where the fluid jet meets gas dynamics opposition, like external atmospheric pressure p_H.

By definitions, the current local force can be written as

$$F_c = F_{cv} - p_H \cdot S, \tag{3}$$

where F_{cv} represents the local force of the current in vacuum, in the absence of atmospheric.

It is known that the local force of the current in vacuum, is the sum of two components, static, $p \cdot S$ and dynamic, $\dot{M} \cdot V$, that is

$$F_{cv} = \dot{M} \cdot V + p \cdot S, \tag{4}$$

where V and p are the absolute local speed, respectively, local static pressure of the fluid.

It is known the expression of the local force of the current in vacuum, based on gas dynamics function of impulse, $z(\lambda)$,

$$F_{cv} = c_f \cdot \dot{M} \sqrt{T^*} \cdot z(\lambda), \tag{5}$$

the constant function c_f, is

$$c_f = \sqrt{2 \cdot \frac{k+1}{k} \cdot R}, \tag{6}$$

where k is adiabatic exponent of fluid evolution, R is gas constant, and λ is Chaplygin number, counterpart of Mach number, relative to flow critical conditions, minimum.

It takes into account that gas dynamics function of impulse is expressed [3] by

$$z(\lambda) = \frac{1}{2}\left(\lambda + \frac{1}{\lambda}\right) \tag{7}$$

and can be plotted based on λ, as in Fig. 2.

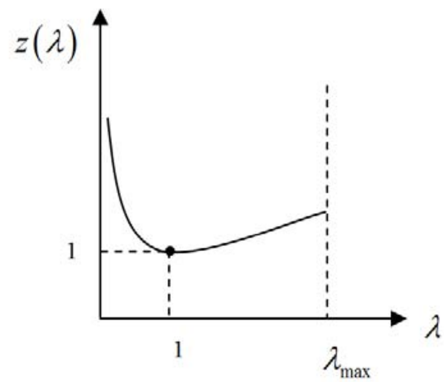

Fig. 2 Gas dynamics function of impulse

Given the important role played by fluid mass flow in achieving thrust force, we use the known local relationship

$$\dot{M} = c_m \cdot \frac{p^*}{\sqrt{T^*}} \cdot S \cdot q(\lambda), \tag{8}$$

where

- c_m is mass flow constant,

$$c_m = \sqrt{\frac{R}{k}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}};$$

- $q(\lambda)$ the gas dynamics function [5] of the mass flow,

$$q(\lambda) = \lambda\left(\frac{k+1}{2} - \frac{k-1}{2} \cdot \lambda^2\right)^{\frac{1}{k-1}}. \tag{9}$$

The graphic, based on λ, the gas dynamics function of the flow has the aspect from Fig. 3.

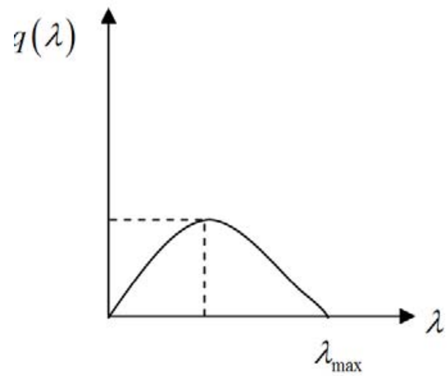

Fig. 3 Gas dynamics function of the flow

Applying equation (5), in the fundamental sections of the generalized nozzle, *e-e* and *i-i*, and the conditions given by the relation (3), then the current local forces becomes primary forms [6].

$$F_{ci} = c_{fi} \cdot \dot{M}_i \cdot \sqrt{T_i^*} \cdot z(\lambda_i) - p_H \cdot S_i \tag{10}$$

and

$$F_{ce} = c_{fe} \cdot \dot{M}_e \cdot \sqrt{T_e^*} \cdot z(\lambda_e) - p_H \cdot S_e \ . \tag{11}$$

So, based on relation (2), the developed force becomes

$$F_i = c_{fi} \cdot \dot{M}_i \left[\frac{c_{fe}}{c_{fi}} \cdot \frac{\dot{M}_e}{\dot{M}_i} \cdot \sqrt{\frac{T_e^*}{T_i^*}} \cdot \frac{z(\lambda_e)}{z(\lambda_i)} - 1 \right] - p_H \cdot S_i \left(\frac{S_e}{S_i} - 1 \right). \tag{12}$$

To simplify writing, we define the input coefficient $\overline{X}$,

$$\overline{X} = \frac{X_e}{X_i},$$

where X is an arbitrary quantity.

As such, it is stated further

- $\overline{\dot{M}} = \frac{\dot{M}_e}{\dot{M}_i}$, coefficient of mass contribution;
- $\overline{T}^* = \frac{T_e^*}{T_i^*}$, coefficient of temperature contribution;
- $\overline{p}^* = \frac{p_e^*}{p_i^*}$, coefficient of mechanical (or pressure) contribution;
- $\overline{S} = \frac{S_e}{S_i}$, coefficient of geometric contribution;

- $\overline{c}_f = \dfrac{c_{fe}}{c_{fi}}$, coefficient of constant impulse;

- $\overline{c}_m = \dfrac{c_{me}}{c_{mi}}$, coefficient of constant mass.

With this notations, relation (12), can be written as

$$F_i = c_{fi} \cdot \dot{M}_i \left[\overline{c}_f \cdot \dot{\overline{M}} \cdot \sqrt{\overline{T}^*} \cdot \frac{z(\lambda_e)}{z(\lambda_i)} - 1 \right] - p_H \cdot S_i \left(\overline{S} - 1 \right). \tag{13}$$

Regarding fluid mass flow, it can be played in two main sections by

$$\dot{M}_e = c_{me} \cdot \frac{p_e^*}{\sqrt{T_e^*}} \cdot S_e \cdot q(\lambda_e)$$

and

$$\dot{M}_i = c_{mi} \cdot \frac{p_i^*}{\sqrt{T_i^*}} \cdot S_i \cdot q(\lambda_i) \ .$$

Under these conditions, the coefficient of mass input has the form

$$\dot{\overline{M}} = \overline{c}_m \cdot \frac{\overline{p}^*}{\sqrt{\overline{T}^*}} \cdot \overline{S} \cdot \frac{q(\lambda_e)}{q(\lambda_i)} \ . \tag{14}$$

Assuming that the sizes are known and given parameters

- mass, - geometrical, - thermal, - mechanics, - kinematics,

in input section, then the problem of determining the force developed by generalized nozzle returns to the question of eliminate kinematics parameters, more exactly, the coefficients of speed in output section, λ_e.

Obviously, from (13)

$$z(\lambda_e) = z(\lambda_i) \cdot \frac{1}{\overline{c}_f} \cdot \frac{1 + \dfrac{F_i + p_H S_i \left(\overline{S} - 1 \right)}{\dot{M}_i \cdot c_{fi}}}{\dot{\overline{M}} \cdot \sqrt{\overline{T}^*}} \tag{15}$$

and, from (14),

$$q(\lambda_e) = q(\lambda_i) \cdot \frac{1}{\overline{c}_m} \cdot \frac{\dot{\overline{M}} \cdot \sqrt{\overline{T}^*}}{\overline{p}^* \cdot \overline{S}} \ . \tag{16}$$

It is, therefore, necessary to settle the conditions which represent relations between the two gas dynamics functions to express the idea of harmonic flow out of the generalized nozzle section.

Of course, a simple, but very complicated, is to express from (15), the

$$\lambda_e = f\left(F_i, \dot{\overline{M}}, \sqrt{\overline{T}^*}, \overline{S} ..... \right)$$

and, from (10),

$$\lambda_e = f\left(\bar{\dot{M}}, \sqrt{\bar{T}^*}, \bar{p}^*, \bar{S}.....\right)$$

then, by equalization, we will obtain

$$F_i = f\left(\bar{\dot{M}}, \bar{T}^*, \bar{p}^*, \bar{S}.....\right).$$

The originality of this paper is to find simple ways of elimination, taking as a basis, the harmony that unites the two gas dynamic functions, $z(\lambda)$ and $q(\lambda)$, under the principle of complementarity, expressed by different laws.

3. The laws of harmony based on the principle of complementarity

Mathematical physics study [7] reveals that there are whole areas such as
- continuum mechanics;
- electromagnetic field theory;
- heat transfer,

which can be treated, with success, by the theory of complex variable functions in the complex plane.

In the case of rotational movements

$$rot\ \vec{V} = 0,$$

and if the velocity of the fluid, $\vec{V}$, is derived from a potential, φ,

$$\vec{V} = grad\ \varphi.$$

Based on the continuity equation, the potential velocity is a harmonic function that satisfies Laplace's equation

$$\Delta\varphi = \frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial y^2} = 0\ . \tag{17}$$

Since the rotor is zero, the vortex has no components, as such, and current function is harmonic, ψ namely

$$\Delta\psi = \frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2} = 0\ . \tag{18}$$

On the other hand, between functions φ and ψ are Cauchy's monogenic conditions.

Therefore, the functions φ and ψ, associated harmonics [8], can be the real and imaginary, of a complex variable analytic functions

$$f(z) = \varphi(x, y) + i\psi(x, y) \tag{19}$$

the variable z is

$$z = x + iy.$$

Transforming Cartesian coordinates to polar coordinates, ρ, θ, then the two functions φ and ψ can be expressed in terms of ρ and θ, the variable z is

$$z = \rho\left(\cos\theta + i\sin\theta\right) = \rho e^{i\theta} .$$

Also, in this coordinate things remain unchanged regarding harmonic functions $\varphi(\rho, \theta)$ and $\psi(\rho, \theta)$.

As, any irotational movement will be represented by an analytical function of *z*, this is available vice versa, any analytic function of complex variable *z* represent an irotational movement.

So, always, an analytic function $f(z)$ will represent complex potential of a well defined movement.

Main functions are

1 $f(z) = z$; 2 $f(z) = \frac{1}{z}$; **3** $f(z) = z^2$; 4 $f(z) = z^3$;

5 $f(z) = z + \frac{1}{z}$; 6 $f(z) = \ln z$; 7 $f(z) = e^z$.

Of these, the most interesting, with a particular physical significance, is the law 3, $f(z) = z^2$, common in fractal geometry (of nature) [8].

Considering that

$$z = x + iy ,$$

then

$$f(z) = (x + iy)^2 ,$$

namely

$$f(z) = \left(x^2 - y^2\right) + 2ixy . \tag{20}$$

Therefore,

$$\varphi(x, y) = x^2 - y^2 , \tag{21}$$

and

$$\psi(x, y) = 2xy . \tag{22}$$

Obviously, the above functions, φ and ψ, shall be harmonic because verify the Laplace equation $\Delta\varphi = 0$ and $\Delta\psi = 0$.

In view of the harmonic character, conjugate, of the functions φ and ψ, aspects of gas dynamic functions $z(\lambda)$ and $q(\lambda)$ as well as the relationship between them, it can be concluded that the main harmonic laws [9] are:

I. $x + y = ct$, linear law, l_l;

II. $y = ct\left(x + \frac{1}{x}\right)$, parabolic law, l_p;

III. $x \cdot y = ct$, hyperbolic law [10], l_h.

Plotting these laws images obtained are those from Fig. 4.

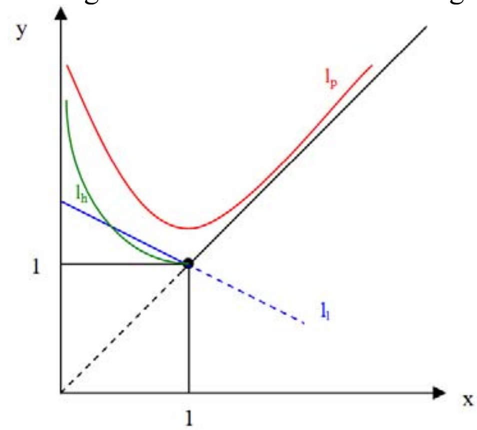

Fig. 4 Harmonic law

This is why, further, it will discuss [11], to make a comparison, each case.

4.1. Linear law

Based on the known [2], from variations of the gas dynamic functions, it is acceptable, for a range of variation of the coefficient λ_e

$$0,4 \le \lambda_e \le 1,$$

that

$$z(\lambda_e) + q(\lambda_e) \approx 2. \tag{23}$$

Taking into account the relations (15) and (16), the form of the resulting thrust force F_I is

$$F_I = \dot{M}_i \left[\alpha_1 \left(\bar{\dot{M}} \cdot \sqrt{\bar{T}^*} - 1 \right) + \beta_1 \left(\frac{\bar{\dot{M}}^2 \cdot \bar{T}^*}{\bar{p}^* \cdot \bar{S}} - 1 \right) + \gamma_1 \left(\bar{S} - 1 \right) + \delta_1 \right], \tag{24}$$

in which

$$\begin{cases} \alpha_1 = 2 \cdot \dfrac{c_{fi} \cdot \overline{c}_f}{z(\lambda_i)} \cdot \sqrt{T_i^*} \\ \beta_1 = -\dfrac{c_{fi} \cdot \overline{c}_f}{\overline{c}_m} \cdot \dfrac{q(\lambda_i)}{z(\lambda_i)} \cdot \sqrt{T_i^*} \\ \gamma_1 = -\dfrac{1}{c_{mi}} \cdot \dfrac{p_H}{p_i^*} \cdot \sqrt{T_i^*} \cdot \dfrac{1}{q(\lambda_i)} \\ \delta_1 = \alpha_1 + \beta_1 \end{cases} . \tag{25}$$

Obviously, because the specific thrust force, F_{SP} is

$$F_{SP} = \frac{F}{\dot{M}_i}, \tag{26}$$

then the nozzle generalized specific thrust force, in case I , becomes

$$F_{SP_I} = \alpha_1 \left(\bar{\dot{M}} \cdot \sqrt{\overline{T}^*} - 1 \right) + \beta_1 \left(\frac{\bar{\dot{M}}^2 \cdot \overline{T}^*}{\overline{p}^* \cdot \overline{S}} - 1 \right) + \gamma_1 \left(\overline{S} - 1 \right) + \delta_1 . \tag{27}$$

4.2. Parabolic law

In this case, replacing the functions, in harmonic parabolic law

$$z(\lambda_e) = c_1 \cdot q(\lambda_e) + \frac{c_2}{q(\lambda_e)} + c_3 , \tag{28}$$

available in subsonic regime, for

$$0,05 \le \lambda_e \le 1 .$$

The values of constants c_i, i=1, 2, 3 depending on the nature of the working fluid.

So,

- for air $c_1 = 0,215$; $c_2 = 0,79$; $c_3 = -0,005$;
- for burned gases $c_1^{'} = 0,235$; $c_2^{'} = 0,797$; $c_3^{'} = -0,032$.

Specific force, developed in case II, has the form

$$F_{SP_{II}} = \alpha_2 \left(\bar{\dot{M}} \cdot \sqrt{\overline{T}^*} - 1 \right) + \beta_2 \left(\frac{\bar{\dot{M}}^2 \cdot \overline{T}^*}{\overline{p}^* \cdot \overline{S}} - 1 \right) + \gamma_2 \left(\overline{S} - 1 \right) + \delta_2 \left(\overline{p}^* \cdot \overline{S} - 1 \right), \tag{29}$$

where

$$\begin{cases} \alpha_2 = h_i \cdot \sqrt{T_i^*} \cdot c_3 \\ \beta_2 = h_i \cdot \sqrt{T_i^*} \cdot c_1 \cdot q(\lambda_i) \\ \gamma_2 = -\frac{1}{a_i} \cdot \sqrt{T_i^*} \cdot \frac{p_H}{p_i^*} \cdot \frac{1}{q(\lambda_i)}, \\ \delta_2 = h_i \cdot \sqrt{T_i^*} \cdot c_2 \cdot \frac{1}{q(\lambda_i)} \end{cases} \quad (30)$$

as $h_i = c_{fi}$ and $a_i = c_{mi}$.

4.3. Hyperbolic law

This case is the most interesting and, also, the easiest, as it pertains to hyperbolic law [11],

$$z(\lambda_e) \cdot q(\lambda_e) \approx 1, \quad (31)$$

valid for a variation of the speed coefficient in the output

$$0{,}1 \le \lambda_e \le 1 .$$

Taking into account the expressions (5) and (8), then, by removing the flow rate is obtained

$$F_{cv} \approx c_v \cdot p^* \cdot S, \quad (32)$$

where

$$c_v = c_m \cdot c_f .$$

Under these conditions, the current force, in reality, becomes

$$F_c \approx c_v \cdot p^* \cdot S - p_H \cdot S . \quad (33)$$

We apply this expression, in the fundamental sections of the generalized nozzle, and obtained, highlighting the parameters the input section, F_{III}

$$F_{III} = \frac{1}{c_{mi}} \cdot \frac{\dot{\bar{M}} \cdot \sqrt{\bar{T}^*}}{q(\lambda_i)} \left[c_{vi} \left(\bar{c}_v \cdot \bar{p}^* \cdot \bar{S} - 1 \right) - \frac{p_H}{p_i^*} \left(\bar{S} - 1 \right) \right]. \quad (34)$$

Specific force, in case III, is written as

$$F_{SP_{III}} = \varepsilon_3 \left[c_{vi} \left(\bar{c}_v \cdot \bar{p}^* \cdot \bar{S} - 1 \right) \right] + \gamma_3 \left(\bar{S} - 1 \right), \quad (35)$$

$$\varepsilon_3 = \frac{1}{c_{mi}} \cdot \frac{T_i^*}{q(\lambda_i)} \cdot c_{vi}$$

$$\gamma_3 = -\frac{1}{c_{mi}} \cdot \frac{T_i^*}{q(\lambda_i)} \cdot \frac{p_H}{p_i^*}$$

where

$$c_{vi} = \frac{1}{c_{mi}} \cdot c_{fi}\,;\; \overline{c}_v = \frac{c_{ve}}{c_{vi}}\,.$$

Obviously, the value of λ_e can be obtained either from the condition

$$z(\lambda_e)\cdot q(\lambda_e) \approx 1\,,$$

either

$$q(\lambda_e) = c_p \cdot \frac{\dot{\overline{M}} \cdot \sqrt{\overline{T}^*}}{\overline{p}^* \cdot \overline{S}}\,,$$

where

$$c_p = \frac{1}{\overline{c}_m} \cdot q(\lambda_i)\,.$$

5. Numerical results and comparisons between models

It is interesting, further, to make a comparison between the results obtained by applying, in these three cases, the models presented, for the same jet engine.

The comparison takes into account assessments of specific thrust forces, F_{SPi}, $i = 1,2,3$, under the same conditions assumed (size, parameters, coefficients) to enter into the system.

It notes that

$$F_{SP1} = F_{SP\,I}\,;\; F_{SP2} = F_{SP\,II}$$

and

$$F_{SP3} = F_{SP\,III}\,,$$

where specific relationships are applied to the entire propulsion system, considered integral generalized nozzle.

All calculations are performed for

- static flying condition, $H = 0$, $V = 0$;
- rated operating conditions.

Thus, is allowed the following input into the engine:

- $p_i^* = p_o = 1{,}01325 \cdot 10^5$ N/m^2;
- $T_i^* = T_o = 288$ K;

and kinematics conditions $q(\lambda_i) = 0{,}81$ and $z(\lambda_i) = 1{,}134$.

Characteristics of the working fluid are

- exponents adiabatic evolutions, through system,
  - air, $k = 1{,}4$;

- gas, $k^{'} = 1,33$;

- specific fluid constants
  - air, $R = 287$ J/kg K;
  - gas, $R^{'} = 287,16$ J/kg K.

Calculating constants we have the following values

- $c_m = \alpha \approx a^{'} = 0,0404$;
- $c_f = h \approx h^{'} = 31,37$;
- $c_v = c_v^{'} = 1,268$;
- $k_1 = k_1^{'} = 24,753$.

Allowed, further, the following input factors, valid for the whole system, holistic:

- $\overline{c}_m \approx 1$; - $\overline{c}_f \approx 1$; - $\overline{c}_v = 1$,

and, respectively,

- $\overline{\dot{M}} = 1,02$; - $\overline{T}^* = 3,2$; - $\overline{p}^* \approx 2,56$, - $\overline{S} = 1,1$.

Proceed to the calculation of specific thrust forces for each model, holistic, harmonic and complementary.

5.1. Linear model

Are calculated

- $\alpha_1 = 888,9$; - $\beta_1 = -373,4$; - $\gamma_1 = 518,38$

and - $\delta_1 = 514,41$.

Substituting in relationship (27), specific thrust force, will get

$$F_{SP1} \approx 859 \text{ m/s}.$$

5.2. Parabolic model

Coefficients are - $\alpha_2 = -2,66$; - $\beta_2 = 91,564$; - $\gamma_2 = 525,06$ and - $\delta_2 = 510$.

Substituting, specific thrust force, from (29) becomes

$$F_{SP2} \approx 945,75 \text{ m/s}.$$

Sometimes you can neglect the first component force, because α_2 is much smaller than the other coefficients, the error that is made is under 2%.

5.3. Hyperbolic model

In this case,

- $\gamma_3 = -413{,}16 \qquad \varepsilon_3 = 413{,}66$.

Therefore specific thrust force from relationship (35) is

$$F_{SP3} \approx 810 \text{ m/s} .$$

6. Conclusions

Based on the proposed models and simulations performed on these three cases, for the three laws, harmonic complementary, linear law, parabolic law and hyperbolic law, some interesting conclusions can be drawn.

Among them, we can retain following:

- Regardless of the model is noted that, the most important ways of achievement of thrust forces (propulsion) includes the use of
  - mass nozzle, when $\dot{M}$ varies ascending;
  - thermal nozzle, when T^* increasing variable;
  - mechanical nozzle, when p^* increasing variable;
  - geometrical nozzle, if section changes, simple convergent versions, or Laval, convergent-divergent;
- Making a force requires the existence, at the entrance to the nozzle, a fluid that has a pulse;
- Coefficient of thermal, $\overline{T}^*$, and mechanical contribution, $\overline{p}^*$, are, usually, correlated, as is the case in the system turbo compressor;
- All models are holistic, allowing evaluation of the overall performance of the engine, taking into account, the relations between engine components;
- After the appearance of the three harmonic laws, closest to reality, which leads to reasonable results with the one existing in literature, is hyperbolic law.

  In relation with this absence, other laws errors are
  - linear law, $4{,}9\%$;
  - parabolic law, $16{,}7\%$;
- The best harmonization law is the hyperbolic law, proven by simplicity of specific force expression results, which confirmed, once again, that the test of truth is simplicity;
- For hyperbolic law observe that

$$F_{SP} = f\left(\overline{p}^*, \overline{S}\right),$$

fundamental performance of a nozzle or, furthermore, of a engine, depends only by substantial variation of

- total fluid pressure;
- working channel section (expansion).

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