THRUSTER PERFORMANCES MODELLING AND PARAMETERS ESTIMATION

P.E. BOURG

S.A. MATRA
B.P. 1
78146 VELIZY VILLACOUBLAY CEDEX - FRANCE

ABSTRACT

This note presents the main results of a study performed under ESOC contract. This study has the purpose to define some software (computer programs) to be use for the determination of the performances of thrusters in operation on satellites already under ESOC control. (Ref. 1).

This study is divided in 2 parts :
- in the first part, one analyses the impact of parameters such as temperature, pressure and aging on thruster behaviour in pulsed as well as in continuous burn mode. From analysis of ground tests results, some mathematical model structures are proposed, concerning mainly the pulse shape and its integrated effect on the S/C (impulse bit). Analysis of satellite flight sequences, in spin and in 3 axes stabilised cases lead to a selection of 4 particular manoeuvres for which data transmitted through telemetry allows identification algorithms to be applied.
- in the second part, a choice of algorithms is made and developed in each case.

Finally, computer programs are given and checked on real telemetry data.

Keywords : thruster modelling parameter identification
S/C sequence analysis.

1. INTRODUCTION

AOCS thrusters may work either in pulsed or in continuous modes according to flight stages : During a continuous mode thrusters are switched on once and work during a sufficient length to reach their steady states. On the contrary, pulsed mode may be defined as a sequence of firings at a given cadence.

A cycle is characterised by two durations :

t_{on} : on time of a thruster

t_c : duration between two firings
- the duty cycle : D.C. = t_{on}/t_c

One studied the impact of parameters like supply pressure (P), chamber temperature, aging and possibly t_{on} and t_c on thrust level (F), and in pulsed mode, on its integral (impulse bit) and Barrycenter (centroïd time).

Definitions are :

$$I_b = \int_o^{tc} F(t)\, dt$$

$$t_z = \frac{1}{I_b} \int_o^{tc} t\, F(t)\, dt$$

F(t), I_b and t_z are chosen because of their direct impact on AOCS performance.

Remark : these 2 definitions give the time of application and the level of the impulsive thrust (or torque) which, in a 1 axis problem, leads to the F(t) applied for $o < t < t_c$.

The results which are summarized here are obtained from an analysis of ground tests (ref. 2) and so the derived models just describe the global behaviour of some thruster parameters. This note contains just some of the models defined in the study.

2. CONTINUOUS MODE ANALYSIS

2.1 Injection pressure influence

It was easy to see that the behaviour of the thrust of the 0.5, 2 and 14 N thrusters versus injection pressure was very similar, an obvious model was : $F = a_o P$

If we calculate $\frac{\Delta(F/F_{max})}{\Delta P}$ for the 3 thrusters

Thruster	.5	2	14 (N)
$\frac{\Delta(F/F_{max})}{\Delta P}$	0.045	0.042	0.033

We can establish that the higher the engine thrust size, the better a thruster works over its entire range of pressure.

2.2 Temperature behaviour

Figures 1 and 2 show the behaviour of chamber temperature and thrust versus time for 0.5 N and 2 N thrusters respectively. One can make 4 main remark :

- both thrusters have a similar behaviour : the steady state temperature is reached very quickly compared with the time to cool to initial conditions. This fact is very important for the pulsed mode modelling because it means that even for very small DC, the thruster cannot get cold between two pulses (in normal pulsed conditions for example when t_{off} 3 sec).
- for a given thruster, heating and cooling times are independant of supply pressure.
- the nominal thrust level is reached in a much shorter time than the steady state temperature.
- steady state temperature increases with the supply pressure.

2.3 Influence of aging

During the OTS project the effect of aging has been partially studied during ground tests on 0.5 and 2 N thrusters. Aging is essentially due to the progressive degradation of the catalyst bed caused by break-up catalyst and loss of catalytic activity.

Qualitatively one notices in continuous and in pulsed mode adiminution of the thrust level and a longer time required to reach the steady state. That means in pulsed mode a greater number of pulses. If we analyse the pulse shape behaviour after several cumulated on times, one notices the degradation of the pulse profile and the decrease of plateau values in quasi steadty state. The aging effect also appears to depend on the engine thrust size. If we compare the thrust level at the beginning of life and after the same cumulated on time for a given pressure, we have very different results between thrusters.

$\frac{\Delta F}{F_{Nom}}$

$P_{(bar)}$ \ $F_{(N)}$	0.5	2	14
22	4.4 %	4.8 %	6.8 %
10	2.1 %	3.8 %	16.6 %
5.5	14.2 %	11 %	31.8 %

$\frac{\Delta F}{F_{Nom}}$ is the relative lost of thrust, with F defined as F_{Nom} - F(real) for a given pressure.

It seems that there is no simple law to explain $\frac{\Delta F}{F_{Nom}}$ as a function of cumulated on time and thrust. This is probably due to engine design parameters :

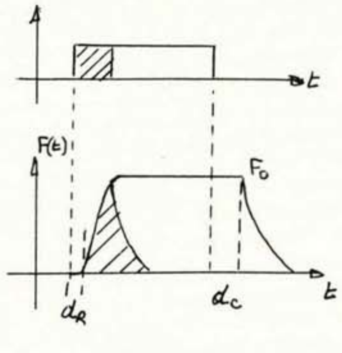
- injection velocity
- P across the bed catalyst
- flow rate per unit area of catalyst bed (bed loading)
- catalyst porosity.

3. PULSED MODE MODELLING

3.1 Pulse profile modelling

3.1.1 Experimental results analysis and model

By studying experimental results we can make the following remarks : the pulse (i.e. a steady state pulse in a pulse train) can be represented by the following profile :

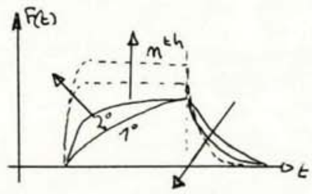


F_o : nominal thrust

d_R, d_C : pure delay

/// : short pulse

We note a sharp rise transient a slower decay transient and a quasi horizontal plateau depending on supply pressure, pulse duration and pulse number. In the same way, for a given pulse train, if we look at the behaviour of thrust profiles versus pulse number (i.e. from 1st pulse (cold pulse) to n^{th} pulse (hot pulse)) we see the following sketch :



First, the thrust profile reaches its steady state form and in a second step the thrust level reaches its nominal value. We verify that from the end of n^{th} pulse to the beginning of the $(n + 1)^{th}$ pulse the thrust level of the plateau does not decrease (no cooling effect) and that for any t_{on} and D.C. we have about the same rise and decay profiles for a given pulse.

We can try to explain these phenomena if we suppose that the rise and decay profiles are due to the chemical reaction speed and to the decomposition of the remaining hydrazine respectively and that the plateau level is due to the cumulated on time (thermal constants are long).

So we propose the following model :

$$\text{if : } o < t < t_{on} : f(n,t) = Fo(n,t_{on})(1-e^{-\lambda 1(n)t})$$

$$t_{on} < t < t_c : f(n,t) = f(n,t_{on})e^{-\lambda 2(n)(t-t_{on})}$$

λ_1 and λ_2 are functions of n and reach limit values λ_1^∞, λ_2^∞.

3.1.2 Determination of parameters

The λ_1, λ_2 and F_o structures were define from qualification test results of the 2 N thruster of OTS.

We choose the F_o function by studying the plateau behaviour in 2 cases :

- long pulses (t_{on} > 1000 msec)

- short pulses (62.5 and 250 msec) for pulse numbers with $\lambda_1 = \lambda_1\infty$ and $\lambda_2 = \lambda_2\infty$ but nominal plateau value not yet reached.

We propose the following model :

$$Fo(n, t_{on}) = F\infty \left(1 - \frac{1}{1 + \lambda_3 n\, t_{on}} + \frac{\lambda 4}{n\, t_{on}^{\ 2}}\right)$$

λ_3 and λ_4 depend on the thruster, F depends on thruster and pressure.

For the λ_1 (n) and λ_2 (n) functions we arrive at a relatively simple form :

$$\lambda_1(n) = \lambda_1\infty \left(1 - \frac{1}{kn + 1}\right)$$

$$\lambda_2(n) = \lambda_2\infty \left(1 - \frac{1}{kn + 1}\right)$$

3.1.3 Model validation

In a first stage we estimated $\lambda_1\infty$, $\lambda_2\infty$ .... for the 2 N thruster. By integrating F one obtains a theoretical $I_b(n, t)$ which can be compared to the real I_b :

with : $\lambda_1\infty = 50 s^{-1}$ $\lambda_2\infty = 46 s^{-1}$ $\lambda_3 = 7 s^{-1}$
$k = 0.8$ $\lambda_4 = 7 \times 10^{-4} s^2$

and $F\infty = 2.1$ N (BOL of 2N thruster).

We have the following results : (hot pulses)

ton/toff (ms)	$\hat{I}_b$ model (Nsec)
1000/2000	2.103
675/2325	1.421
250/750	.529
150/1850	.319
62.5/1927	.142

I_b experimental (Ns)	Δ%
2.085	.9 %
1.40	1.5 %
0.542	2.4 %
0.33	3.3 %
0.14	1.4 %

We also calculated $\lambda_1\infty$ and $\lambda_2\infty$ for the 0.5 N thruster and $I_b(n)$ in steady state :

t_{on}/t_{off} (ms)	I experiment (NS)	$\hat{I}$ model (NS)	Δ%
75/1925	0.068	0.066	3
150/1850	0.127	0.122	4
300/2700	0.246	0.237	4
675/	0.535	0.524	2
1000/2000	0.788	0.178	2
3000/3000	2.306	2.304	0
5000/5000	3.837	3.835	0

with $\lambda_1\infty = 40\ sec^{-1}$, $\lambda_2\infty = 29\ sec^{-1}$ $F\infty = .77$ N- (B.O.L.)

P = 22 bar.

In both cases we have a good agreement

3.2 Centroïd time versus pulse number modelling

The simplest model we found which takes good account of $t_z(n)$ at a given pressure is :

$$t_z(n) = t_z\infty \left(1 + \frac{\mu^1(n, t_{on})}{1 + n\mu_2(n, t_{on})}\right)$$

If we want a simple solution we may try to choose :

n : $\mu 1(n, t_{on}) = \mu 1(t_{on})$
n : $\mu 2(n, t_{on}) = \mu 2(t_{on})$: $t_z(\infty) = t_{z\infty}$

This hypothesis has been validated with the 14 N thruster. For a pulse train with $t_{on} = 100$ ms, we have found : $\mu 1 = .595$, $\mu 2 = 1.205$

Pulse number	1	2	3	10	50	∞
t_z experimental	108	99	96	90	86	85(ms)
t_z model	108	99.8	95.96	88.87	85.82	85
error %	0	0.8	0.04	0.14	0.2	0

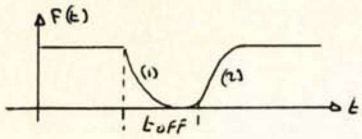
We note a very good similarity.

We have the same similitude with a $t_{on} = 500$ msec ($\mu_1 = 3.87$, $\mu_2 = 24.66$).

We did not have enough experimental data to study μ_1 and μ_2 as functions of t_{on}.

3.3 OFF modulation modelling

This model is easy to obtain if we consider that the "negative impulse bit" for a given off time is due to the "negative pulse" defined as follows :



(1) Decay profile equal to the decay profile of a normal pulse with an on-time equal to t_{off}.
(2) Rise profile equal to the rise profile of the same normal pulse.

The normal pulse profile must be taken for n = ∞ because the thruster is in its steady state configuration.

So we have the same model as in section 3.1.

$0 < t < t_{off}$ $\quad F(t) = F\infty\, e^{-\lambda 2\infty t}$

$t > t_{off}$ $\quad F(t) = F\infty(1 - e^{-\lambda_1\infty(t-t_{off})})$ I

In the case of 0.5 thruster we had (see section 3.1) $\lambda_1\infty = 40\ sec^{-1}$, $\lambda_2\infty = 29\ sec^{-1}$, $F\infty = .77$ N.

By integrating equations I for several off times we obtain the following results :

OFF TIME	150	300	676 ms
I_b experimental	.127	.245	.535 Ns
I_b model	.131	.231	.512 Ns
%	3.1 %	5.7 %	4.2 %

4. FLIGHT SEQUENCE ANALYSIS

In the second part of the study we tried to define which thruster parameter can be identified by using the telemetry during each flight sequence of a S/C. (3 axis or spin stabilized). In our case the main problems to be solved are :

- the input determination and choice : because most of the algorithms are based on a comparison between model and process outputs, we have to be sure that, at the same time, the inputs are similar in both cases. Now since in the case of a spinner S/C, the control is generally operated in open loop, the inputs are known directly. It is not the same for 3 axis stabilised satellites, the control laws are in closed loop and either we have enough information in the available outputs and on the con trol actuators to perform the identification or we have to simulate the inputs and all the control, leading to much more sophisticated algorithms and models. Another point is the sensitivity of the parameter values to input variations. In most cases natural inputs are "poor" for an identification purpose. In our case it is of course impossible to add an extra input signal to improve the sensitivity of the identification.
- model structures
  even when we assume that the structure of the model is good and that the convergency of the algorithm is perfect, we cannot avoid errors due to the relative knowledge of parameters such as lever arm, inertia, relative positions of sensors and actuators. The impact of these errors depends on the sophistication of the model.
- output determination
  the convergency of most algorithm is based on the decreasing of a cost function. This decreasing has only a sense if we have an adequate accuracy of the available outputs. Because most processes are dynamicsl ones an identification is only possible if the available data takes the dynamics into account. In our case these points lead to the problem of T.M. quantification and sampling rate.

4.1 manoeuvre selection

From this analysis it appears that most of flight sequences are not suitable for an identification of the model parameters. This is, in most case due to lack of information on pulse duration or dating and to the telemetry quantification and samplig rate.
In case of 3 axis S/C the pulse duration and data is generally determined on board in closed loop and are not telemetered because of their small interest for the users of the S/C.
For both type of S/C the small duration of most of the pulses and thus the small S/C attitude transient makes significant the uncertainty due to quantification or sampling rate, even this uncertainty is enhanced by the detectors noise when low sampling rate is used.
It was meanwhile possible to select 4 particular sequences, which are :

- in 3 axis stabilised case (with fixed on board momentum wheel)
  . nutation motion in normal mode of operation (from IRES roll TM)
  . wheel unloading (from IRES pitch TM)
- in spin stabilised case
  . spin axis reorientation
  . north-south station keeping
- the first manoeuvre leads to the identification of each thrust impulse bit during a two pulses actuation sequence. The second manoeuvre leads to the identification of the impulse bit as a function of pulse number in the wheel unloading thrust actuation train.
- the third manoeuvre to the identification of some of the parameters of the thrust profile model, and the last one to the identification of the quasi steady state thrust in continuous burn.

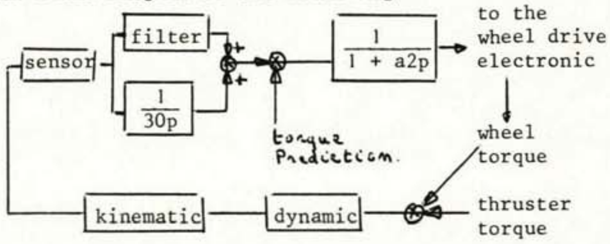
The identification algorithms are based on a comparison between the model outputs and the real telemetry values which allows the building of a quadratic cost function. The decrease of this criteria is performed by using non linear programing methods.

5. TYPICAL EXAMPLE

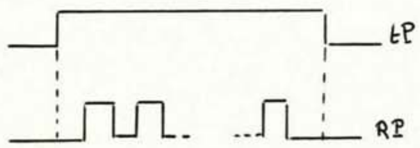
As an illustration of the developped algorithms we summarize here the case of the wheel unloading manoeuvre.

5.1 Principle of the manoeuvre

Due to external torques on the pitch axis the stored kinetic momentum of the wheel increases and reaches a maximum value.
The wheel is then unloaded by applying a well defined sequence of thruster pulses.
The block diagram is the following :



A torque prediction is incorporated in the loop in order to minimise the pitch transient response due to the dynamics of the loop.
The torque prediction is the following with respect to the real pulses :



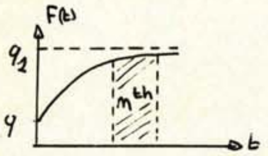
The prediction signal starts is before the 1st real pulse and ends 1s after the last one at a continuous level. Because the impulse bit of the real pulse is a function of pulse number, the prediction torque is not equal to the real one, so we have a pitch behaviour function of the difference between the 2 torques.
We have a 1 axis problem with a well defined sequence of thruster pulses.

5.2 available data

By TM have the pitch output of the sensor with a good sampling rate (1.6s) with respect to the integrated time constant (90 s). The quantification itself is good with respect to the integrated effect, on 2 s of the torques. It leads (before the integrator effect) to more than 5×10^{-2} deg. pitch transient and the quantification is 2×10^{-3} deg. For all these reasons, one may propose an identification of the average effect of each pulse and identify the impulse bit as a function of pulse number.

5.3 Model structure

Due to the response time of the loop we identifie the parameter of a mean torque model :

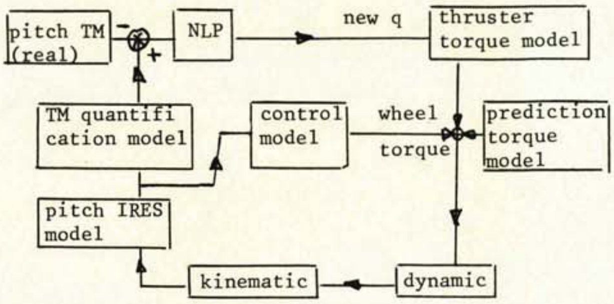


$$F = q_1 + q_2 e^{-q_3 t}$$

corresponding to the average effect of each pulse in the pulse train.

5.4 Identification algorithm

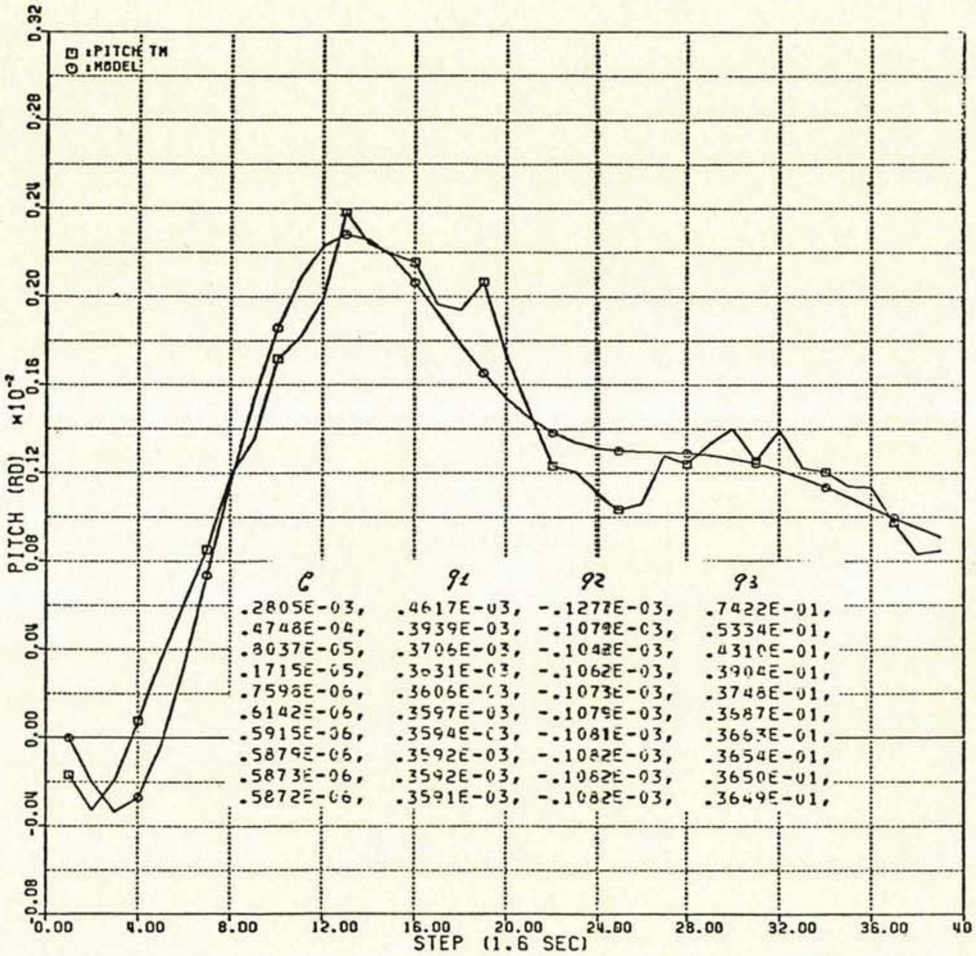
The identification is based on a comparison between the real pitch TM and the model response : the algorithm is sumarized by the following block-diagram :



5.5 Typical results

Figure (1) presents for the beginning of an unloading manoeuvre the real output and the model one. A good similarity can be observed.

C : represents the quadratic cost function value at each step of the convergency process.
$(q_1 - q_2 - q_3)$ the current values of the searched parameters.



C	q1	q2	q3
.2805E-03,	.4617E-03,	-.1277E-03,	.7422E-01,
.4748E-04,	.3939E-03,	-.1079E-03,	.5334E-01,
.8037E-05,	.3706E-03,	-.1042E-03,	.4310E-01,
.1715E-05,	.3631E-03,	-.1062E-03,	.3904E-01,
.7596E-06,	.3606E-03,	-.1073E-03,	.3748E-01,
.6142E-06,	.3597E-03,	-.1079E-03,	.3687E-01,
.5915E-06,	.3594E-03,	-.1081E-03,	.3663E-01,
.5879E-06,	.3592E-03,	-.1082E-03,	.3654E-01,
.5873E-06,	.3592E-03,	-.1062E-03,	.3650E-01,
.5872E-06,	.3591E-03,	-.1082E-03,	.3649E-01,

The reached values correspond to a mean pulse defined by :
thrust : 1.95 N
impulse bit : 0.123 Nsec.

This values may be compared to the ground test results which are : thrust : 2 N
impulse bit (hot case) 0.128 Ns.

6. CONCLUSION

This study defines mathematical models of thrust profile of thrusters in operation on ESA satellite in orbit. The analysis of the flight sequences of a spin and 3 axes stabilised satellites show that it is possible to identify some of the model parameters in some particular phases. Identification program are developped for thruster performance analysis in these particular phases, and tested on real flight data.

Some of the runs performed with the current edition of the identification program have shown that it was possible to explain some particular points of the control loops behaviour (problem of the loop stifness for example) by varying only some control parameters, the identified thruster parameters remaining very similar from a case to another. This could be a possibility of improvement of the study.

7. REFERENCES

1- ESOC contract n° 3855/79 "Assessment of thruster performance"
2- OTS project - 0.5 N thruster qualification test report
2 N thruster qualification test report. ERNO doc. nb : OTS/55/TR/0835 and 836/ERN.