Study and Development of Throttleable Hybrid Rocket Motors

Alessandro Ruffin

Centro di Ateneo degli Studi e Attività Spaziali "Giuseppe Colombo"

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Outline

- Hybrid rocket motors throttleability general considerations
- Flow control valve design
- Flow control valve characterization
- Static hybrid rocket motor fire tests
- Throttling fire tests
- Conclusion and future work

Throttleable Hybrid Rocket Motors

Nammo test, Spartan Project

For a fixed nozzle throat, throttleability is achieved by controlling the oxidizer flow ⇒ Flow control valve (FCV)

Advantages

- Increase trajectory efficency
- Peculiar mission profiles requiring deep throttling
- Requires to control a single feeding line

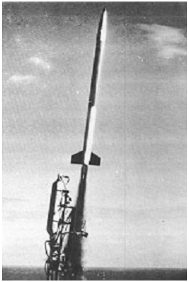
Applications

- Launchers
- ADV
- Flying test beds

Disadvantages

- Increase system complexity
- o/f shifting

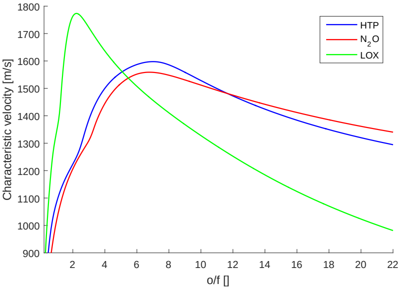
HRM applications



c^* Penalties

- Circular port
- Port fuel consumpion
- Marxman power law

$$o/f = \frac{\dot{m}_{ox}^{1-n}\ D_{port}{}^{2n-1}}{4^n\ \pi^{1-n}\ a\ \rho_f\ L}$$



$$n = 0.5 \ \Rightarrow no\ D_{port}\ sensitivity$$

$$n = 1 \ \Rightarrow no\ \dot{m}_{ox}\ sensitivity$$

$$n \in [0.45\ 0.8]$$

	$90\%HTP$	N_2O	LOX
Maximum c^* [m/s]	1598	1559	1773
c^* Sensitivity [m/s]	−22.4	−16.3	−369.9
c^* Penalty TR=5 (balanced)	95.3%	95.9%	96.2%
c^* Penalty TR=5 (fuel rich)	88.0%	84.5%	82.7%
c^* Penalty TR=10 (balanced)	91.6%	92.8%	93.2%
c^* Penalty TR=10 (fuel rich)	78.3%	78.5%	75.4%

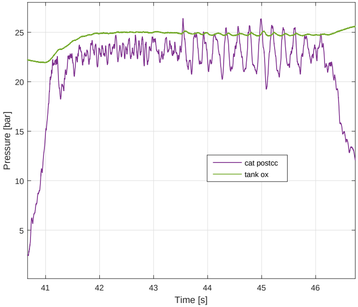
Arbitrary throttling ⇒ o/f shift ⇒ Performance reduction

FCV design

The flow control valve design is based on variable area cavitating venturi

$$\dot{m}_{ox} = C_d \; A_{th} \sqrt{2 \; \rho_{ox} \left(p^{\circ} - p_{sat} \right)}$$

- variable area $\Rightarrow$ flow control
- if $p^{\circ}_{down} < MABPr \cdot p^{\circ}_{up} \;\; \Rightarrow$ tank - combustion chamber uncoupling

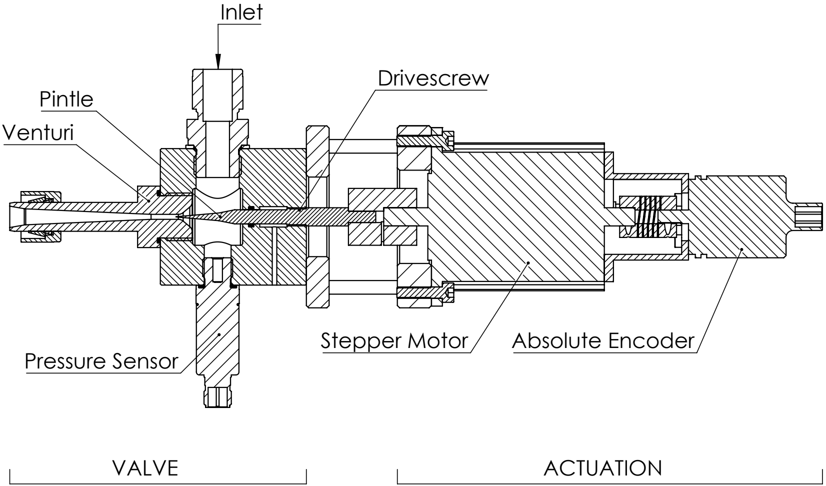


Minimum mass flow range	30 $[g/s]$
Maximum mass flow range	300 $[g/s]$
Maximum operating pressure	80 $[bar]$
Venturi throat diameter	2.2 $[mm]$
Upstream throat radius	3.3 $[mm]$
Venturi divergence angle	5 $[deg]$
Pintle apex angle	10 $[deg]$
Maximum pintle stroke	11 $[mm]$
Useful pintle stroke	7 $[mm]$

- Suitable for HTP
- Conical pintle
- Classic venturi

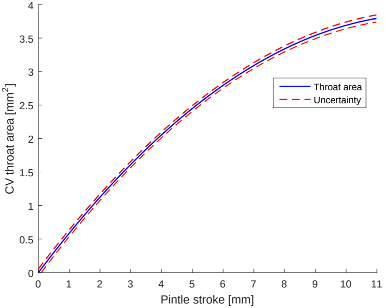
FCV: Design

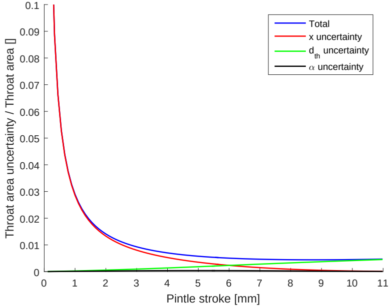
The flow control valve design is based on variable area cavitating venturi



FCV: Design

$$A_{th}(x) = \pi \left(2\left(R_{th} + R_{up}\left(1 - \cos\alpha\right)\right)\sin\alpha \;\; x - \sin^2\alpha \;\; \cos\alpha \;\; x^2\right)$$





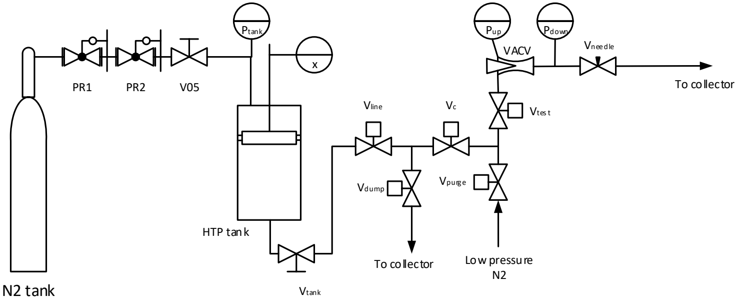
$$\alpha \to 0 \;,\; R_{th} \to +\infty \Rightarrow \text{Increase linearity}$$

FCV characterization: Outline

- Static characterization: *Mass flow and discharge coefficient vs. pintle stroke*
- Maximum allowed back pressure: *Trend with the pintle stroke*
- Cavitation instabilities: *Downstream peak frequency trend*
- Dynamic characterization: *Dynamic behavior of the FCV*

The characterization test campaign was performed using 91% *HTP*

FCV characterization: Set-up

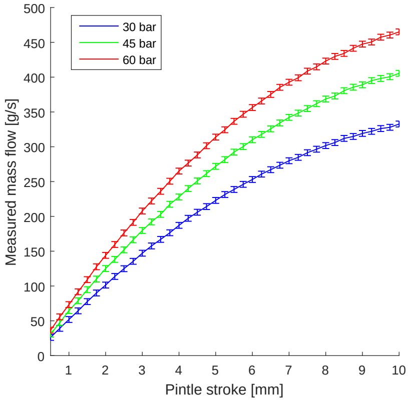


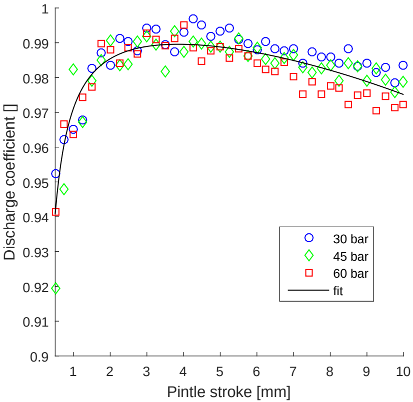
Features

- High pressure N_2 tank
- Pressure regulators
- HTP tank (piston separator)
- Test ball valve
- Flow control valve
- Needle valve
- Purging line

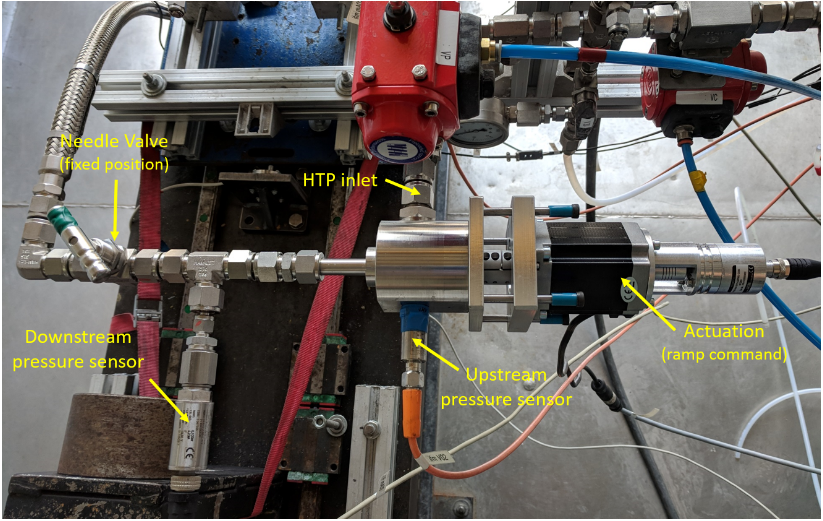
FCV characterization: static characterization

Determine the characteristic of the FCV with the pintle stroke and upstream pressure



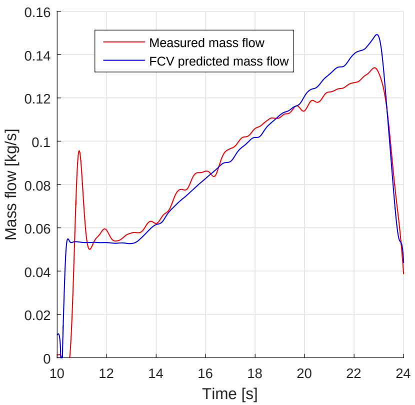


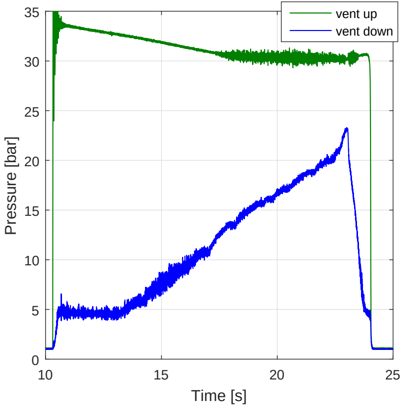
FCV characterization: MABP ratio



FCV characterization: MABP ratio

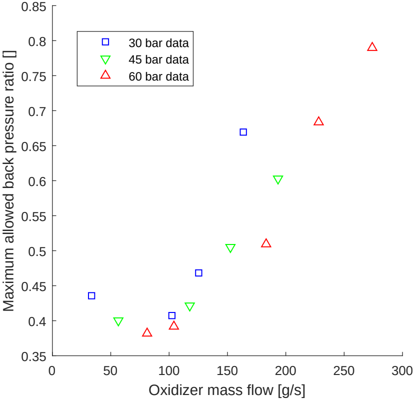
FCV ramp command and fixed needle valve position

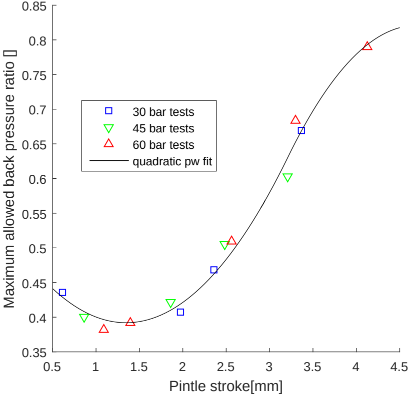




Mass flow data filtered at 5 *Hz*

FCV characterization: MABP ratio



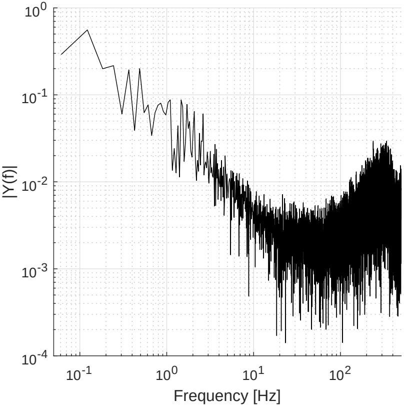


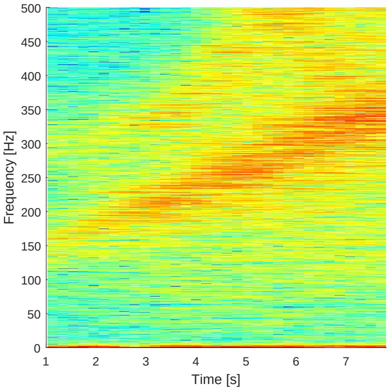
$$\text{MABP ratio} = 0.51649 - 184.95\ x + 68677\ x^2 \qquad \text{for } x \in \left[0.5 \cdot 10^{-3}, 3.2 \cdot 10^{-3}\right[\ m$$

$$\text{MABP ratio} = -1.0871 - 813.24\ x - 86658\ x^2 \qquad \text{for } x \in \left[3.2 \cdot 10^{-3}, 4.5 \cdot 10^{-3}\right]\ m$$

FCV characterization: cavitation instabilities

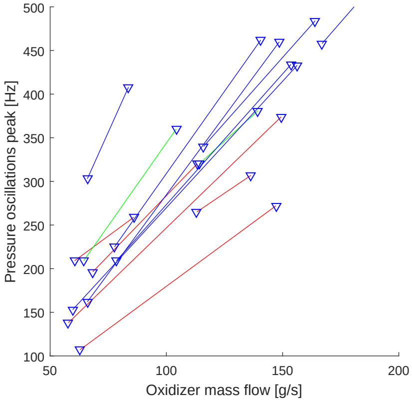
- Downstream pressure sensor spectrum and spectrogram
- Same tests set-up used for MABP characterization

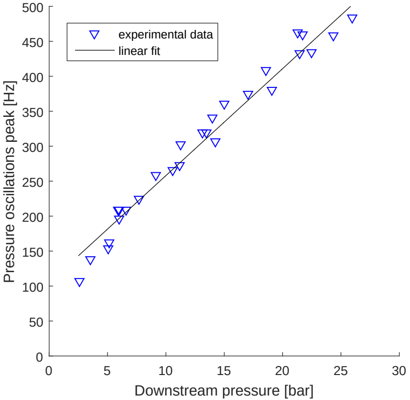




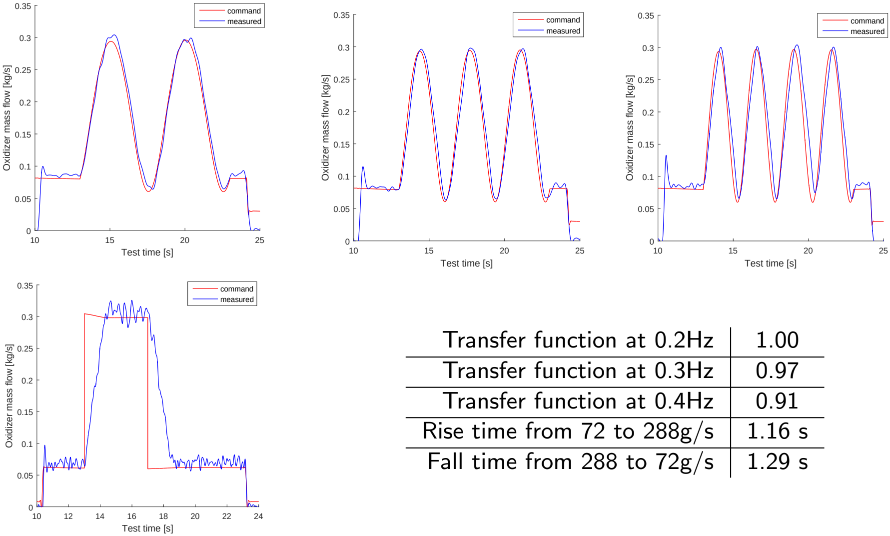
FCV characterization: cavitation instabilities

- Peak frequencies determined from the spectrograms (linear trend)
- Good correlation with the downstream pressure





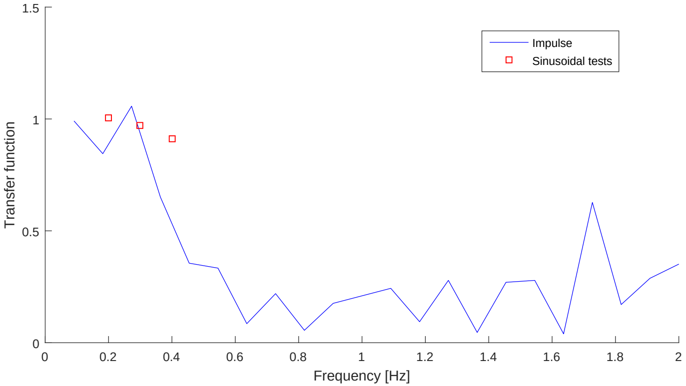
FCV characterization: dynamic characterization



Transfer function at 0.2Hz	1.00
Transfer function at 0.3Hz	0.97
Transfer function at 0.4Hz	0.91
Rise time from 72 to 288g/s	1.16 s
Fall time from 288 to 72g/s	1.29 s

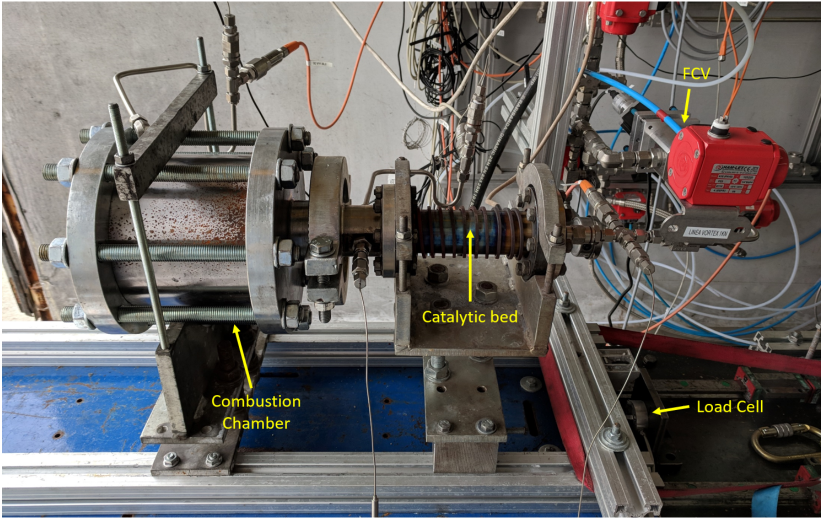
FCV characterization: dynamic characterization

Transfer function between command and measured mass flows



* Band width for a rectangular impulse of 4s length is 0.25Hz

Fire tests: Set-up

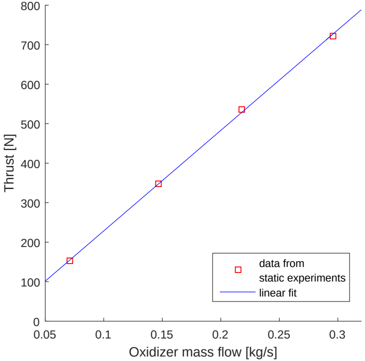


Preliminary fire tests

Four static fire tests were carried out

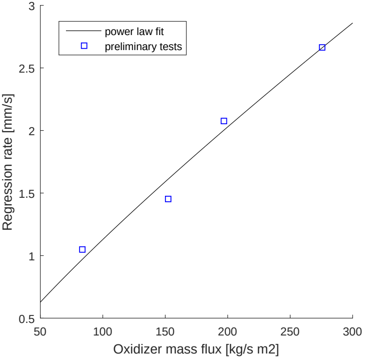
Objectives

- Regression rate
- Motor efficiency with oxidizer mass flow
- Evaluate motor behavior for a wide range of oxidizer flows



Reference test	$\dot{m}_{ox}$ $[g/s]$	t_b $[s]$	$D_{p,fin}$ $[mm]$	p_{cc} $[bar]$	T $[N]$	η $[\%]$
Test #1 — 60	71	12.4	46	9.86	153.3	95.2
Test #2 — 140	147	10.3	50	19.96	347.0	95.5
Test #3 — 220	218	8.4	55	30.90	536.3	95.4
Test #4 — 300	296	6.5	54	36.44	722.3	94.8

Preliminary fire tests



Power law fit of the regression rate

$$\dot{r} = 3.384 \cdot 10^{-2} \cdot G_{ox}^{0.78}$$

- Goodness of fit $R^2 = 0.92$
- Power law exponent $n = 0.78$

$\Rightarrow$ low throttling sensitivity
$\Rightarrow$ high port diameter sensitivity

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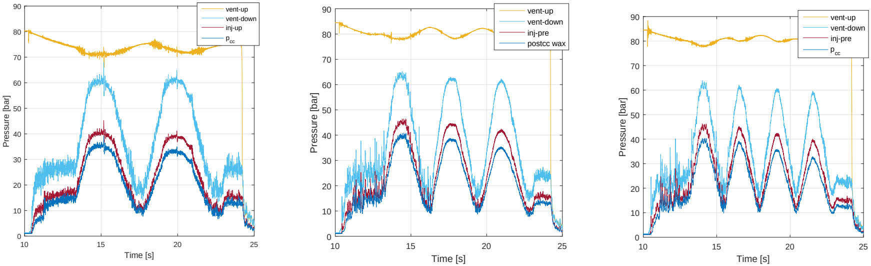
Throttling fire tests

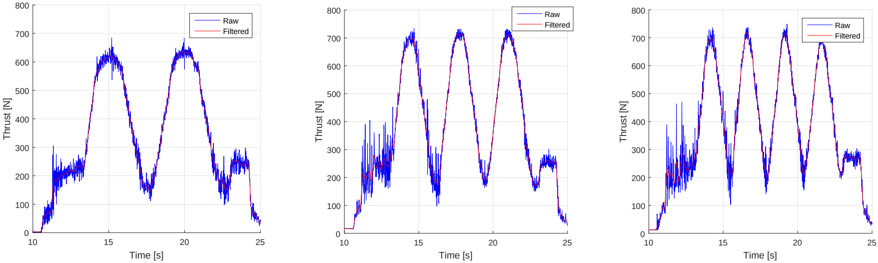
Three sine wave command tests



Reference test	$D_{p,in}$	$D_{p,fin,m}$	$D_{p,fin,c}$	T_{min}	T_{max}	TR
Test 025, 0.2Hz	$20mm$	$55.6mm$	$57.9mm$	$149N$	$634N$	4.26
Test 033, 0.3Hz	$20mm$	$58.1mm$	$59.9mm$	$171N$	$712N$	4.16
Test 034, 0.4Hz	$20mm$	$57.7mm$	$59.8mm$	$202N$	$719N$	3.56

Throttling fire tests

Three sine wave command tests



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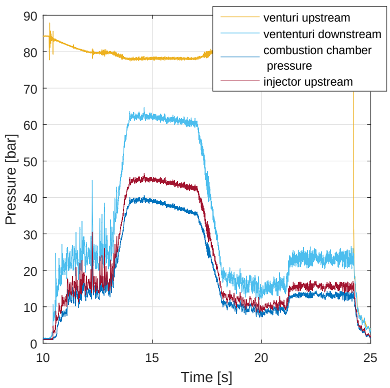
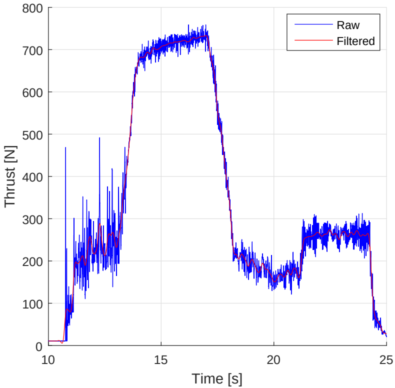
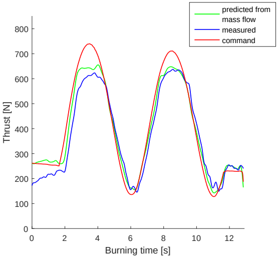
Throttling fire tests

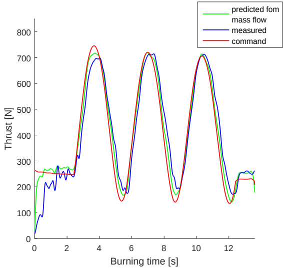
4s square impulse command test

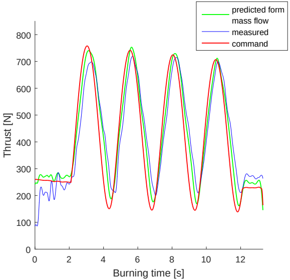


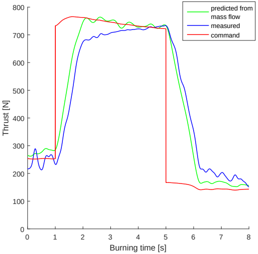


Throttling fire tests





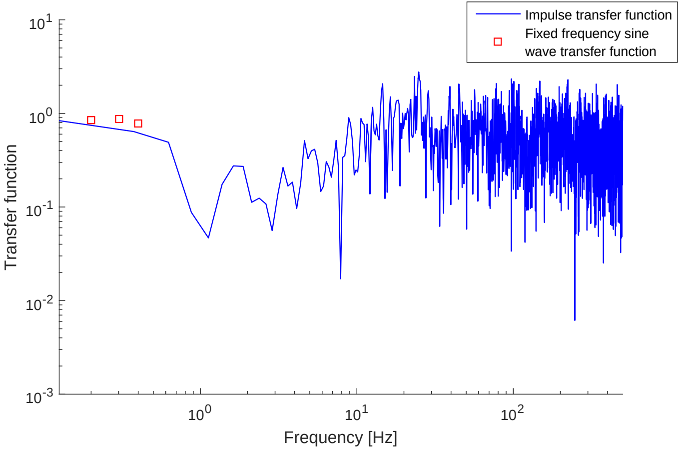




Transfer function at 0.2Hz	0.849
Transfer function at 0.3Hz	0.876
Transfer function at 0.4Hz	0.779
Rise time from 250 to 730N	=
Fall time from 720 to 170N	=

Throttling fire tests: dynamic characterization

Transfer function between command and measured thrust



*Band width for a rectangular impulse of $4s$ length is $0.25Hz$

Conclusion and Future work

- A flow control valve for hybrid rocket motors was developed and characterized
- Our test motor was tested with four different oxidizer mass flows
- Dynamic throttling fire tests were performed reaching a throttling ratio of 4.2 with a maximum thrust of 720N
- FCV-HRM coupled system transfer function and reaction times
- Increase the FCV reaction time
- Implement throttleability in our 7kN test motor

Conclusion

Thank you! Any question?