Combustion Instabilities and Oscillations in Solid Propellant Rockets

F.E.C. Culick

California Institute of Technology

Joint Propulsion Conference

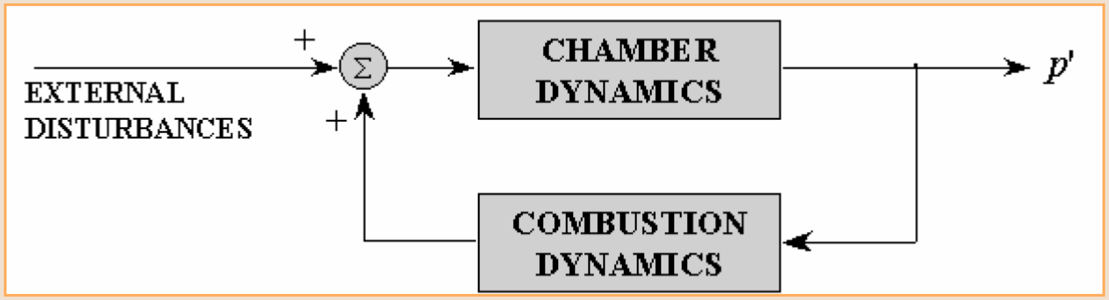
12 July 2006

http:/ /www.culick.caltech.edu

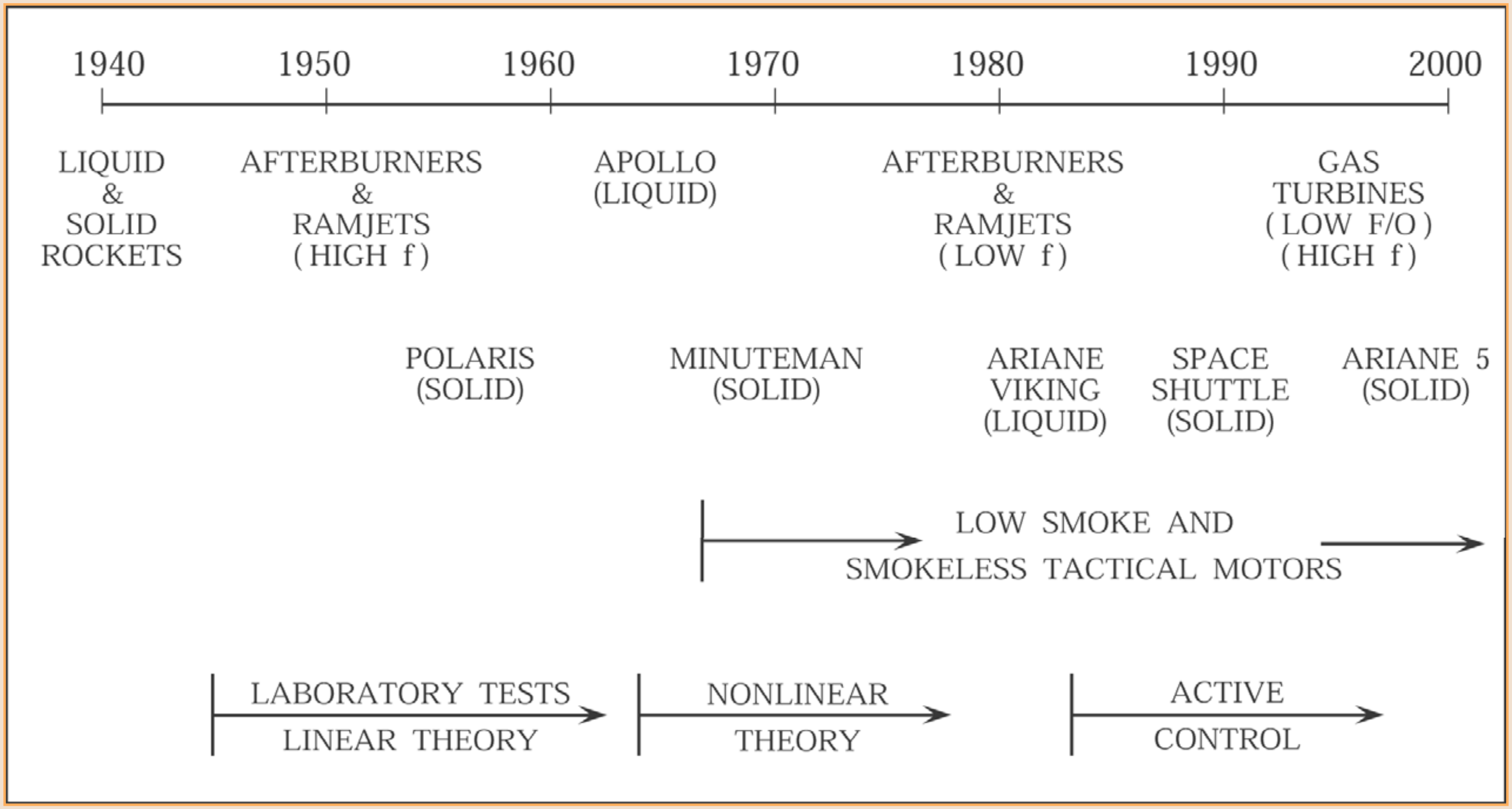
Outline

- Introduction And Background
- Some Examples
- The Primary Mechanism And Its Measurement
- The Main Mechanisms
- Passive Control
- Influences Of Noise
- Laser-based Measurement Of The Primary Mechanism
- Concluding Remarks

Combustion System as a Feedback Amplifier



A Chronology of Combustion Instabilities

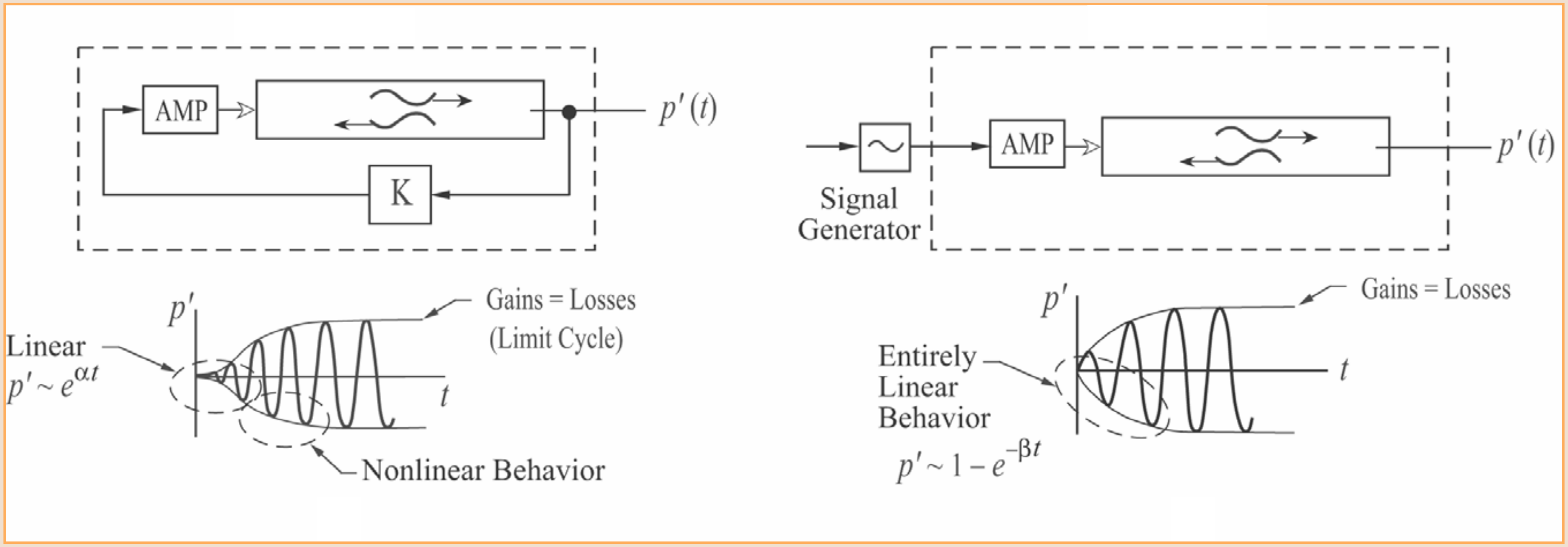


Combustion Instabilities in some U.S. Motors (1951-1997)
Blomshield (2000)

Motor Details					Type				Fix			
No.	Name	Date	App.	Propellant Type	Long	Tang	DC shifts	Pulsed	Prop	Metal	Geo.	Details
1	Sergeant	1951	Sounding	Polysulfide/AP		X						Not fixed
2	RVA-10	1951	TBM	Polysulfide/AP		X						Unknown
3	Sergeant	1957	TBM	Polysulfide/AP		X						Not Fixed
4	Subroc	1961	SAS	Al/Polyurethane	X		X			X		Reduced Al size
5	Iroquois	1960	?	Aluminized	X		X			X		Increased Al%, reduced Size
6	Tartar	1961	SAA	Duel Grain	X		X	X			X	Nozzle moved downstream
7	Tow	1964	STS	Double Base		X	X				X	Added Baffles
8	Genie	1965	ATA	AP/Al/Polyurethane	X					X		Reduced Al size
9	Minuteman	1968	BAL	Double Base/AP/Al	X					X		Changed system, not motor
10	Manpads	1969	SL	AP/Al/HTPB	X		X		X			Lowered Solid Loading
11	ATR	1975	ATA	AP/HTPB		X	X		X			Increased AP size, added catalyst
12	AALM	1975	RES	AP/HTPB				X	X			ZrC containing motors were better
13	MK-12	1975	SAA	AP/Al/HTPB	X	X						Changed system, not motor
14	Slufae	1975	STS	AP/HTPB	X	X					X	Added helmholtz resonator
15	Sidewinder	1977	ATA	AP/HTPB	X		X	X	X		X	Grain design change, some RDX for AP
16	Maverick	1977	AS	AP/HTPB		X	X		X			Increased AP size, added catalyst, ZrC
17	LCMM	1978	RES	AP/HTPB	X		X				X	Add eroding Nozzle, changed geometry
18	MSM	1978	RES	Double Base/CMDB		X	X				X	Increased port area
19	Harm	1978	AS	AP/HTPB	X						X	No changes required
20	EX-70	1979	SAA	AP/HTPB	X				X		X	Smaller AP, increase nozzle size
21	EX-104	1985	SAA	Duel AP/Al/HTPB	X							No changes required
22	ASROC	1985	SAS	AP/HTPB	X							No changes required
23	Sentry	1985	TBM	AP/Al/HTPB	X		X			X		Program ended, smaller Al
24	LCPM	1988	???	AP/HTPB		X			X			Smaller AP, higher loading
25	SHUTTLE	1990	BOS	AP/Al/PBAN	X							No changed required
26	DBM	1994	SL	AP/Al/HTPB	X		X				X	Grain design change
27	Pathfinder	1996	SPA	AP/Al/HTPB	X				X	X		Increased Al from 2% to 16%
28	NWR	1997	RES	AP/HTPB	X	X	X	X	X		X	Stability additives, geometry, pressure

TBM – Theater Ballistic Missile SAS – Surface Anti-Submarine SAA – Ship Launched Anti-Aircraft STS – Surface to Surface SPA – Space Motor
ATA – Air-to-Air BAL – Ballistic Missile SL – Surface Launched AS – Air to Surface RES – Research Motor BOS – Space Booster

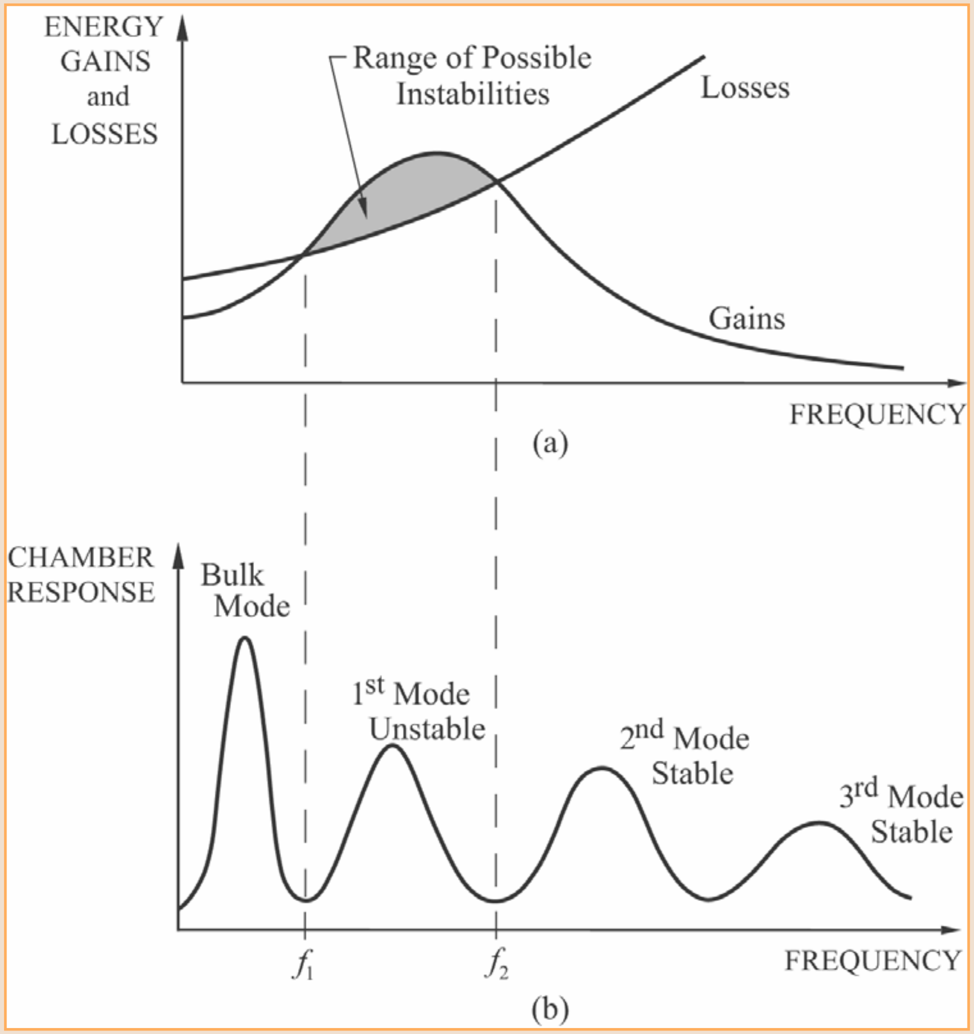
Transient Behavior in a Laboratory Device



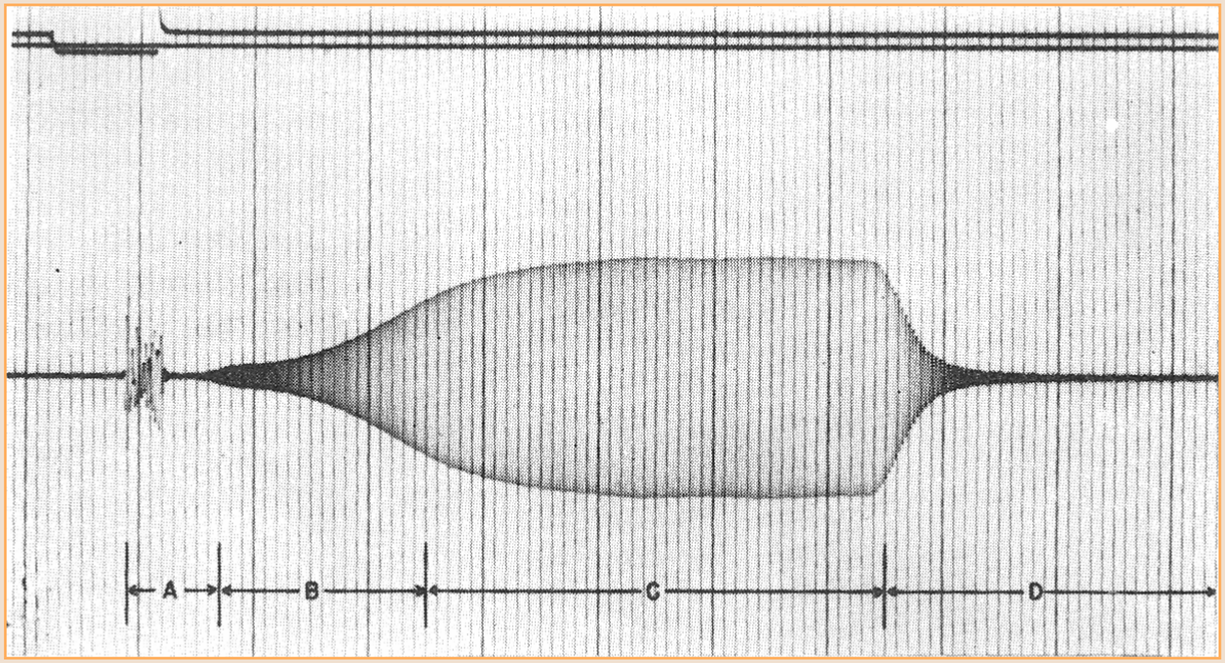
Self-Excited

Driven

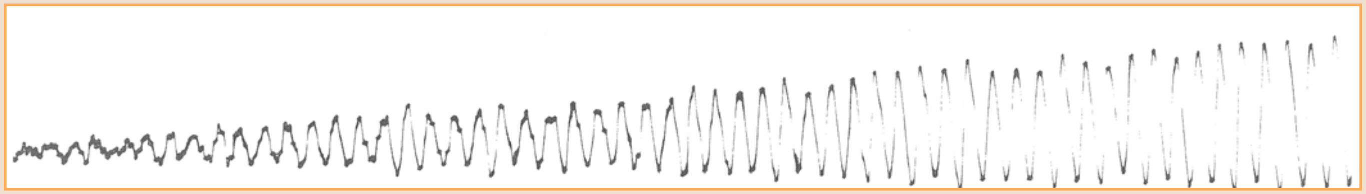
Basic Behavior in Solid Propellant Rockets

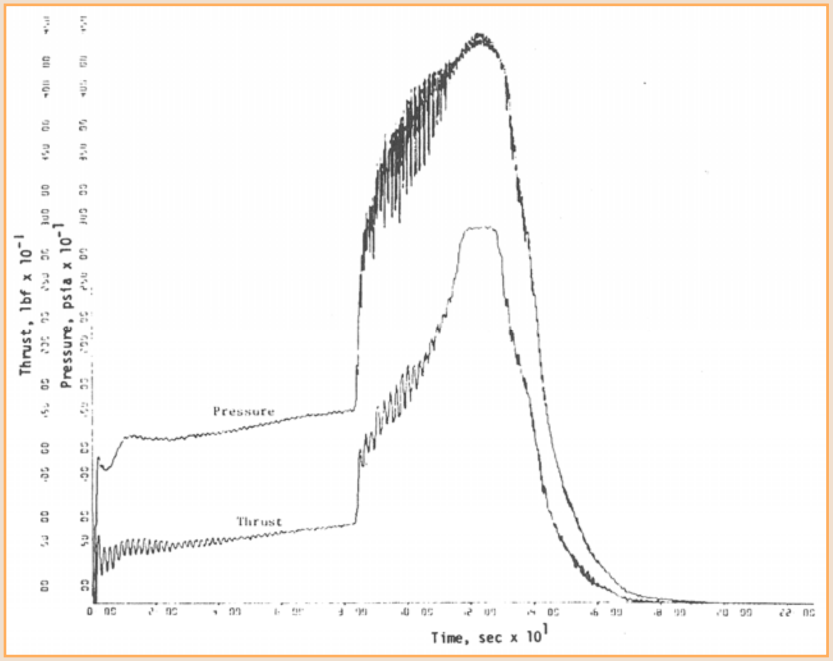


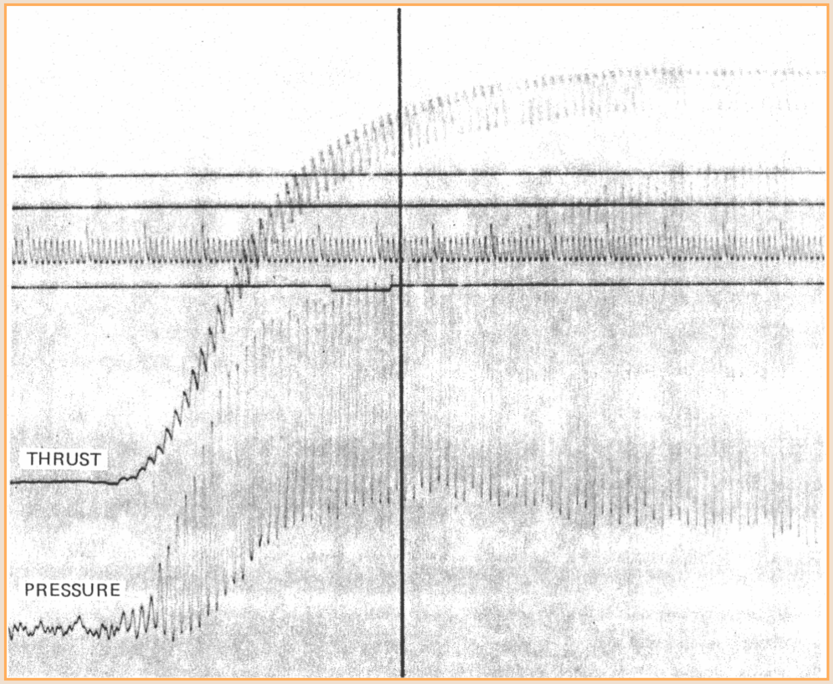
Pressure Record for a T-Burner (Horton and Price 1962)



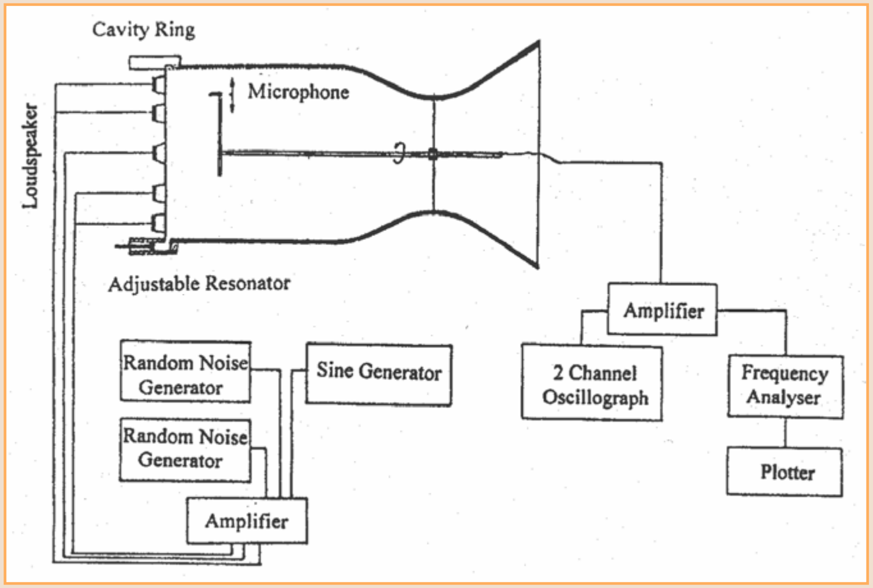
Transient Growths and "Limit Cycles" of Combustion Instabilities

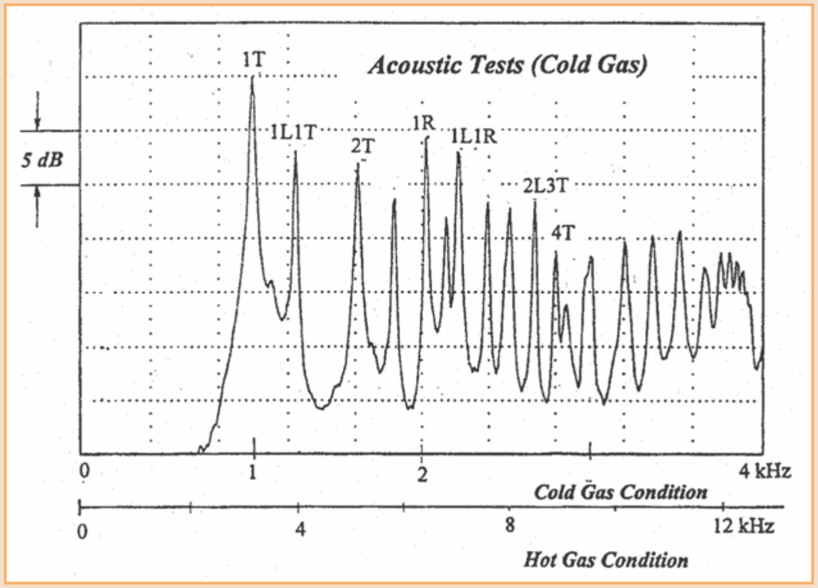




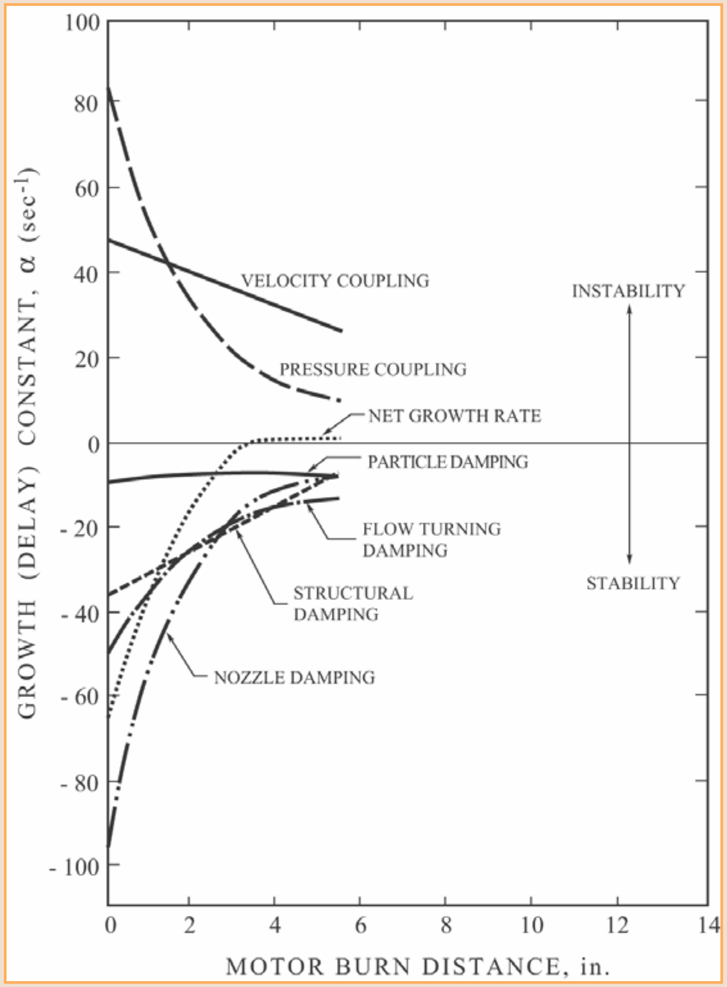


A Model Of A Rocket Chamber And The Meeasured Spectrum (Laudien et al., 1995)





Predicted Stability Boundary For A Large Solid Propellant Rocket Motor (Beckstead 1974).



A Summary of the Instability Problem in 1970

CHAMBER VOLUME

ANALYSIS

GAS DYNAMICS; ACOUSTICS
CALCULATION OF MODE SHAPES
LINEAR STABILITY
NONLINEAR BEHAVIOR
ATTENUATION BY PARTICLES
RESIDUAL BURNING

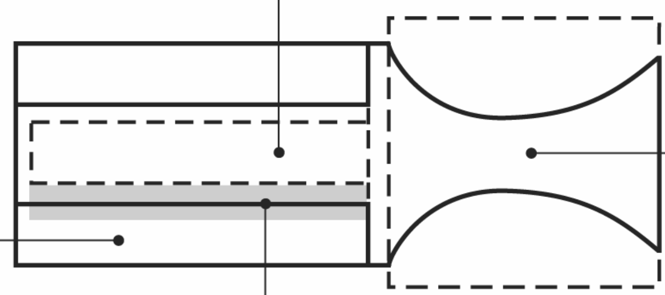
MEASUREMENTS

COLD FLOW ACOUSTICS
SUB-SCALE TESTS
PULSE TESTING
STABILITY
LIMITING AMPLITUDES
SUPPRESSION DEVICES

PROPELLANT GRAIN

ANALYSIS

MODE STRUCTURE
DISSIPATION OF ENERGY
MEASUREMENTS
DYNAMICAL PROPERTIES



NOZZLE

ANALYSIS

ANALYSIS
ADMITTANCE FUNCTION
MEASUREMENTS
COLD FLOW ACOUSTICS

COMBUSTION ZONE

ANALYSIS

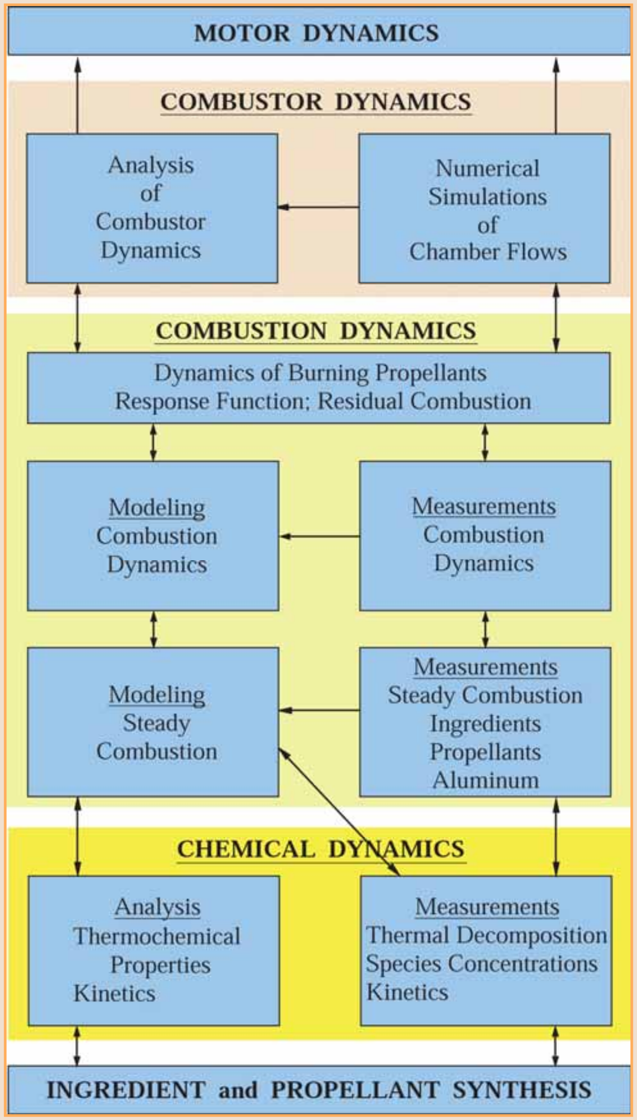
STEADY-STATE BURNING
TRANSIENT RESPONSE
RESPONSE FUNCTIONS
VELOCITY COUPLING
INFLUENCE OF METAL ADDITIVES

MEASUREMENTS

T-BURNERS
ROTATING VALVE BURNERS
MICROWAVE DATA
L*BURNERS
CENTER-VENT MOTORS
SUB-SCALE MOTOR TEST
WIDOW BOMBS

Laser-Based Methods (1981-?)

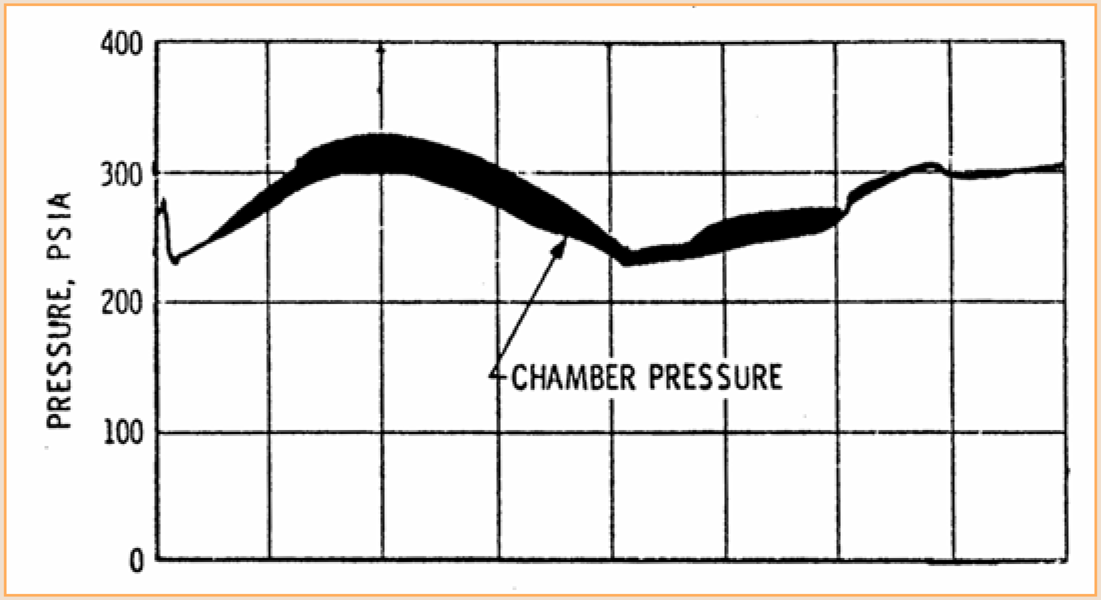
One View of Research Areas and Their Connection



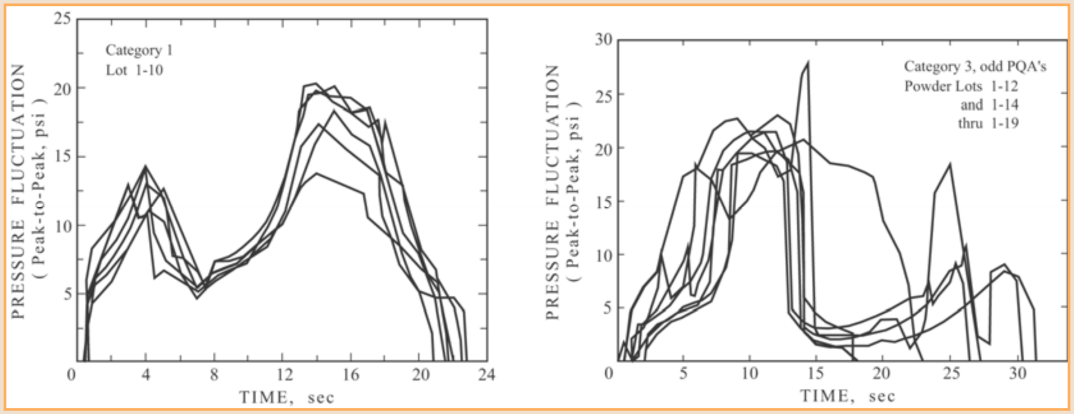
Outline

- Introduction And Background
- Some Examples
- The Primary Mechanism And Its Measurement
- The Main Mechanisms
- Passive Control
- Influences Of Noise
- Laser-based Measurement Of The Primary Mechanism
- Concluding Remarks

Flight Test Record Of Pressure In A Minuteman II, Stage 3.



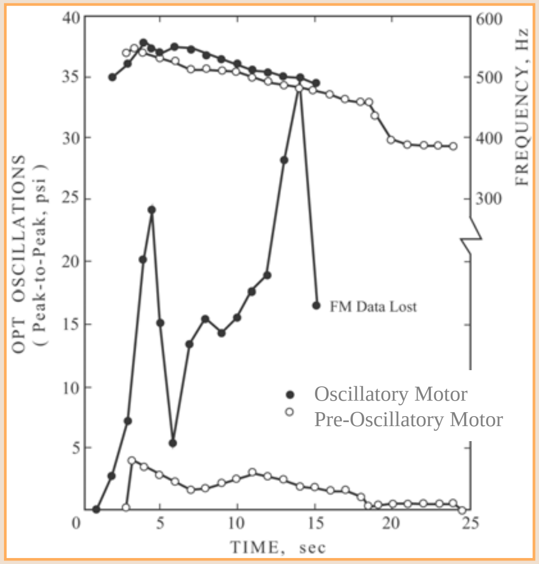
Frequencies and Amplitudes of Combustion Instabilities in the Minuteman II, Stage 3 Motor



(a) Change of behavior after Lot 1-10 (Fowler and Rosenthal 1971)

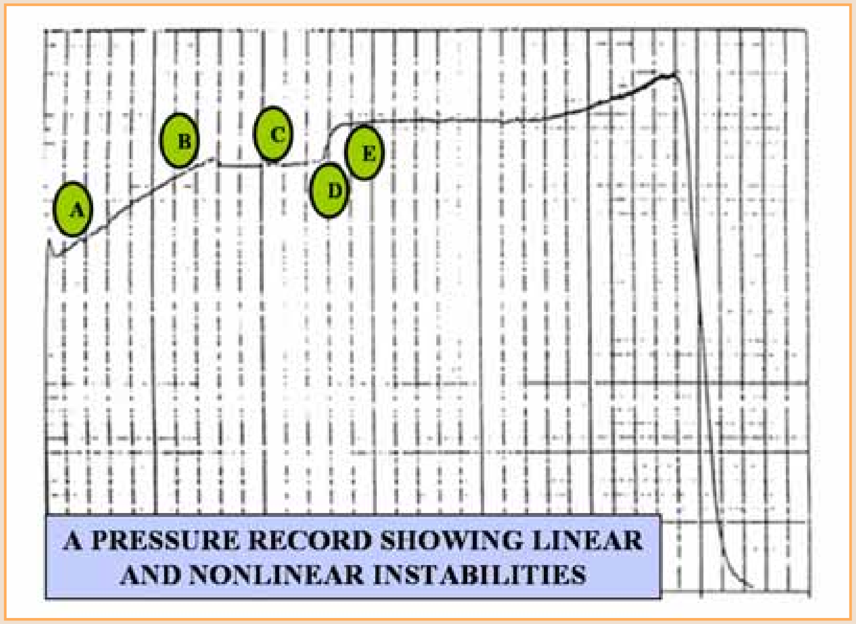
•Earliest example of sensitivity to small changes of composition

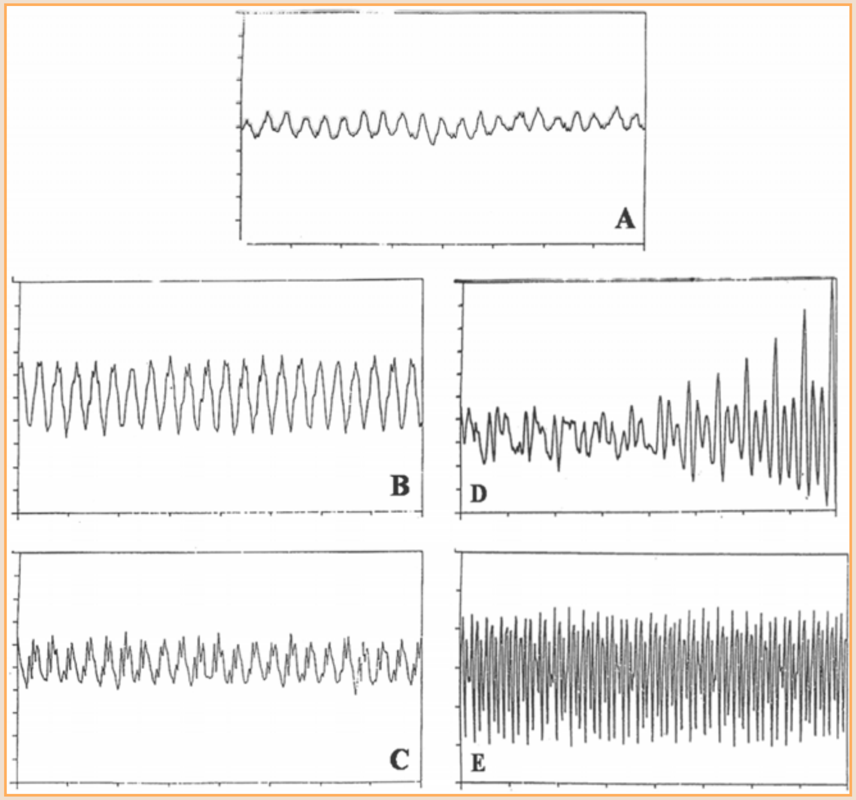
•The large practical problem motivated research for c. 10 years



(b) Frequencies and amplitudes measured during flight tests (Bergman and Jessen 1971)

A Nonlinear Instability in a Tactical Motor

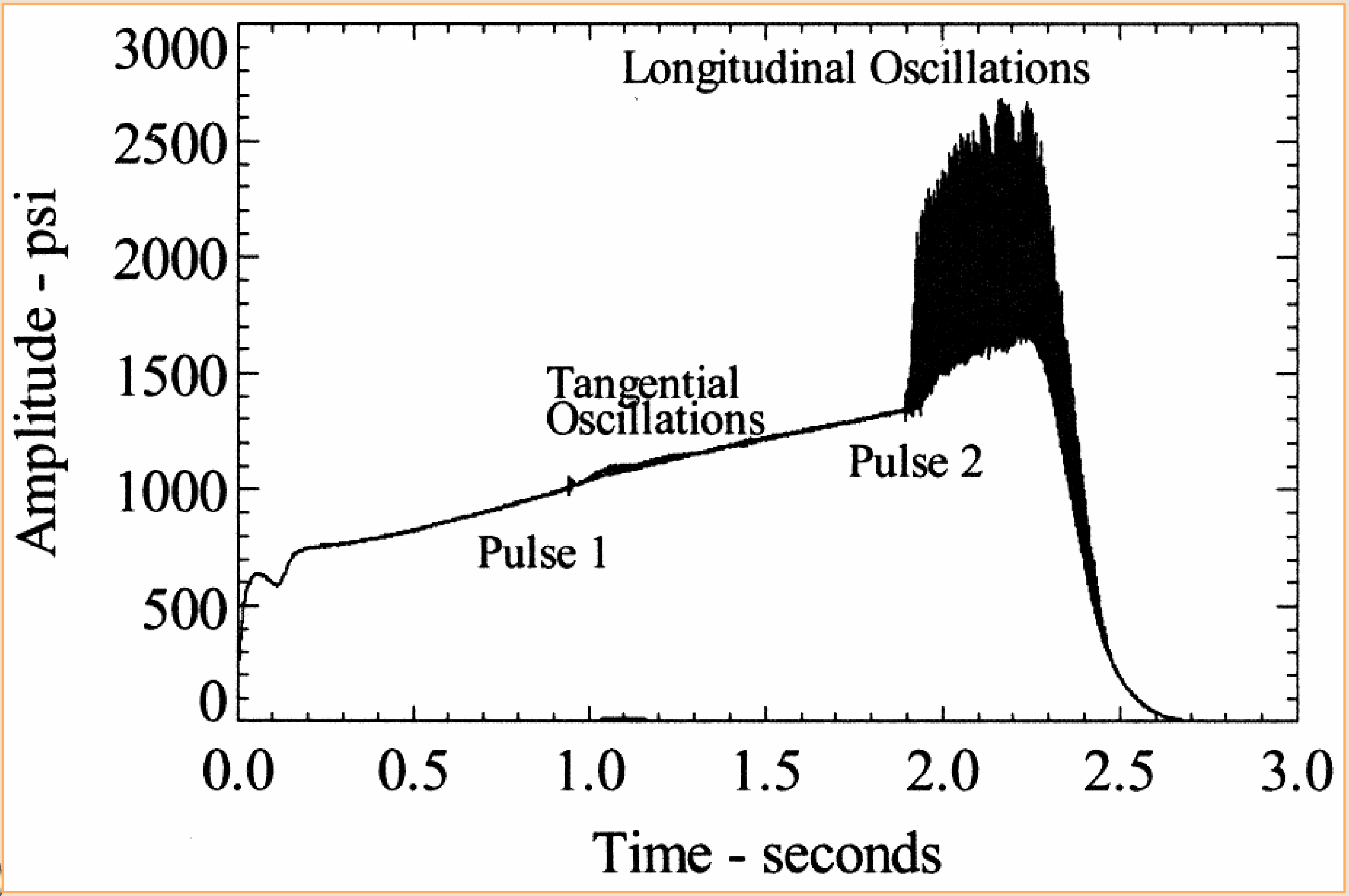




•Changes of unsteady behavior D-E are companied by abrupt rise of mean chamber pressure

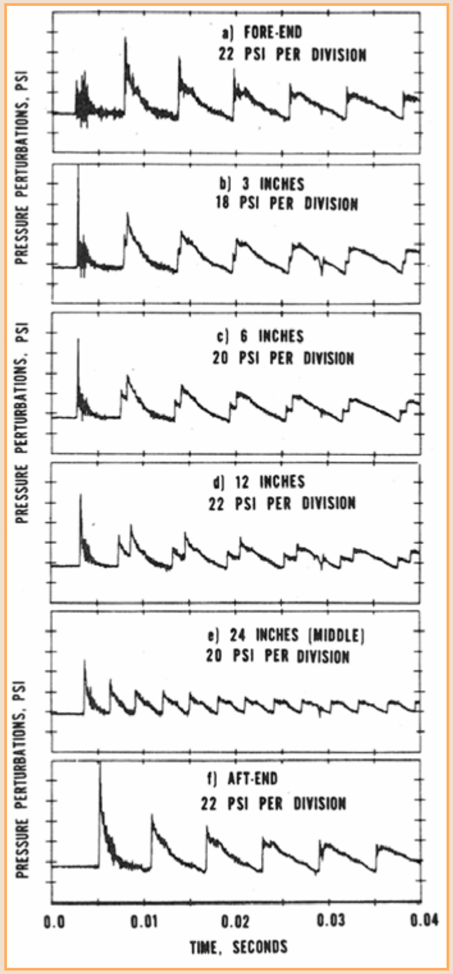
•Unsteady behavior may be due to the mean flow field as well as the response of burning to the flow field

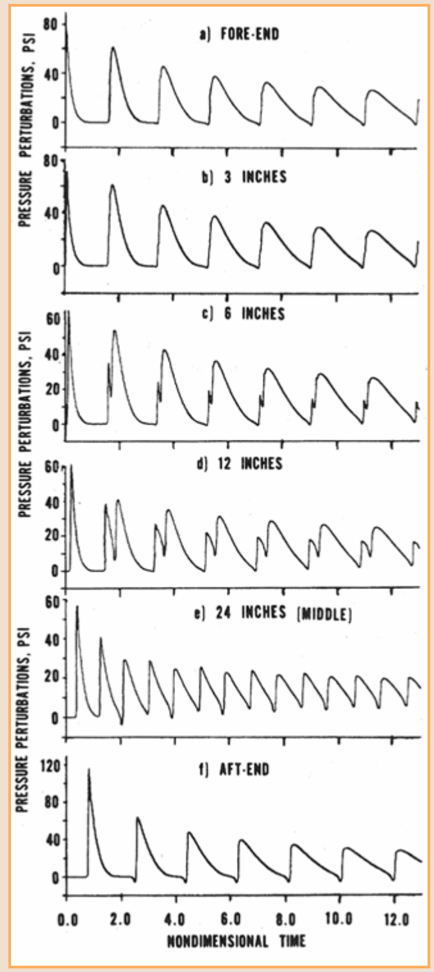
An Example of a Subcritical Bifurcation (Blomshield 2001)



Courtesy of F. Blomshield, NWAC

Time Evolution Of Pressure Perturbations Produced By A Pyro Pulser. (a) Measured; (b) Calculated (Baum, Lovine, and Levine 1983)

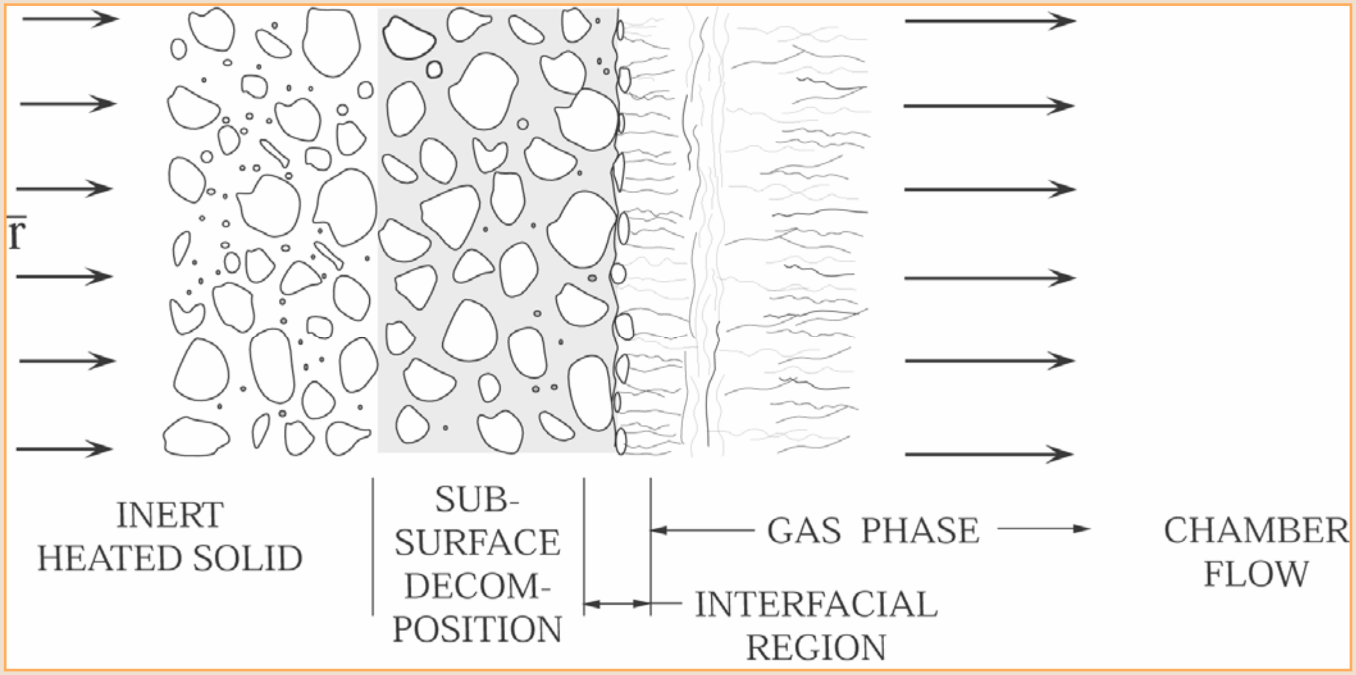




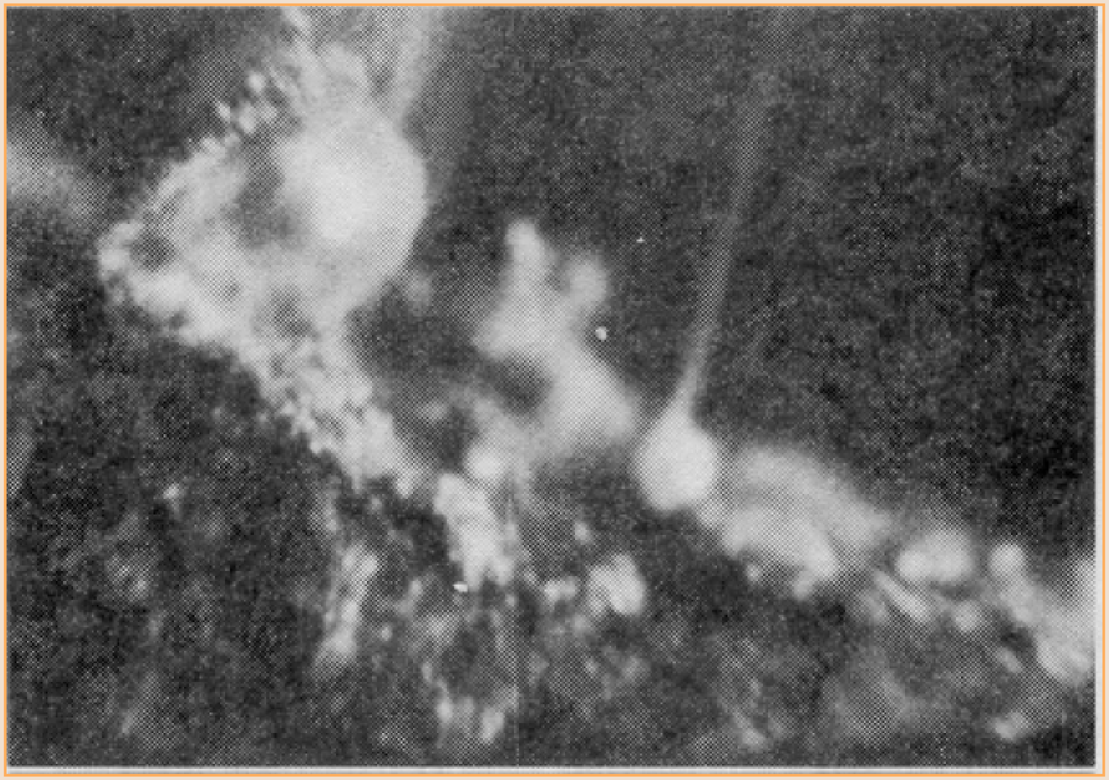
Outline

- Introduction And Background
- Some Examples
- The Primary Mechanism And Its Measurement
- The Main Mechanisms
- Passive Control
- Influences Of Noise
- Laser-based Measurement Of The Primary Mechanism
- Concluding Remarks

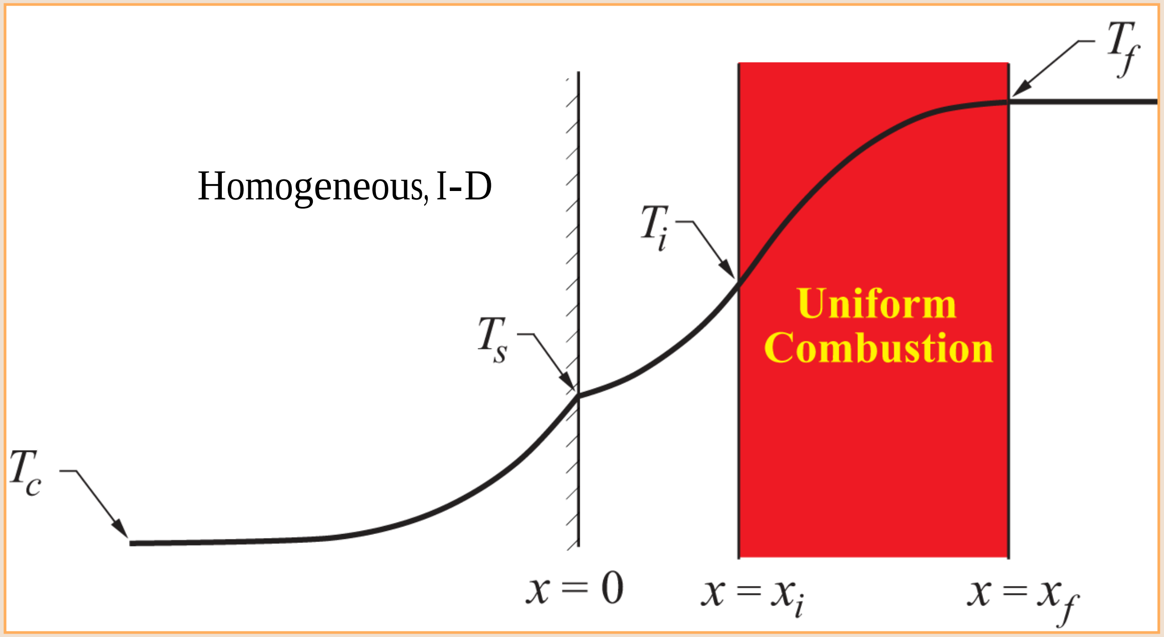
Sketch of Steady Combustion of a Solid Propellant



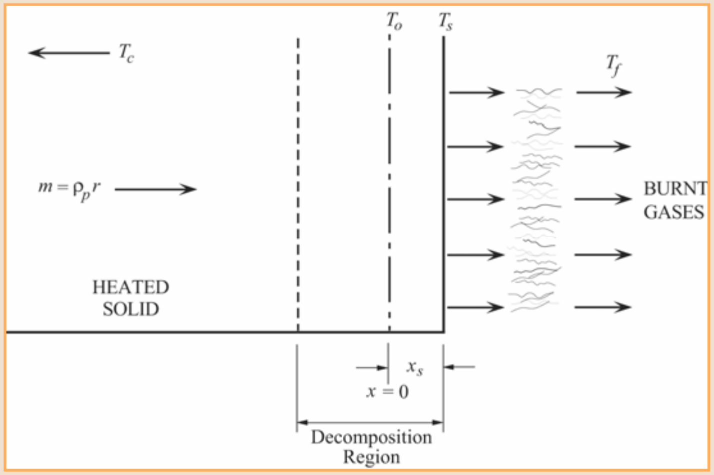
View Of The Surface Of A Burning Solid Propellant Containing Aluminum (Price Et Al. 1982)

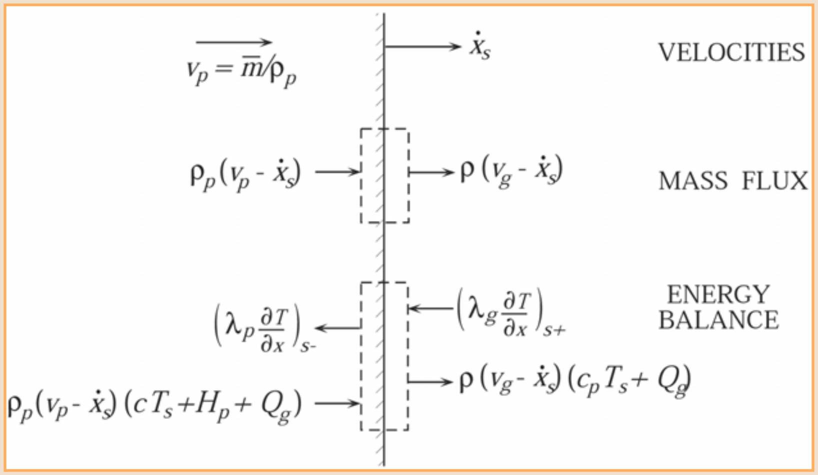


Sketch of the QSHOD Model with Uniform Combustion



Reference System and Matching Conditions for the QSHOD Model

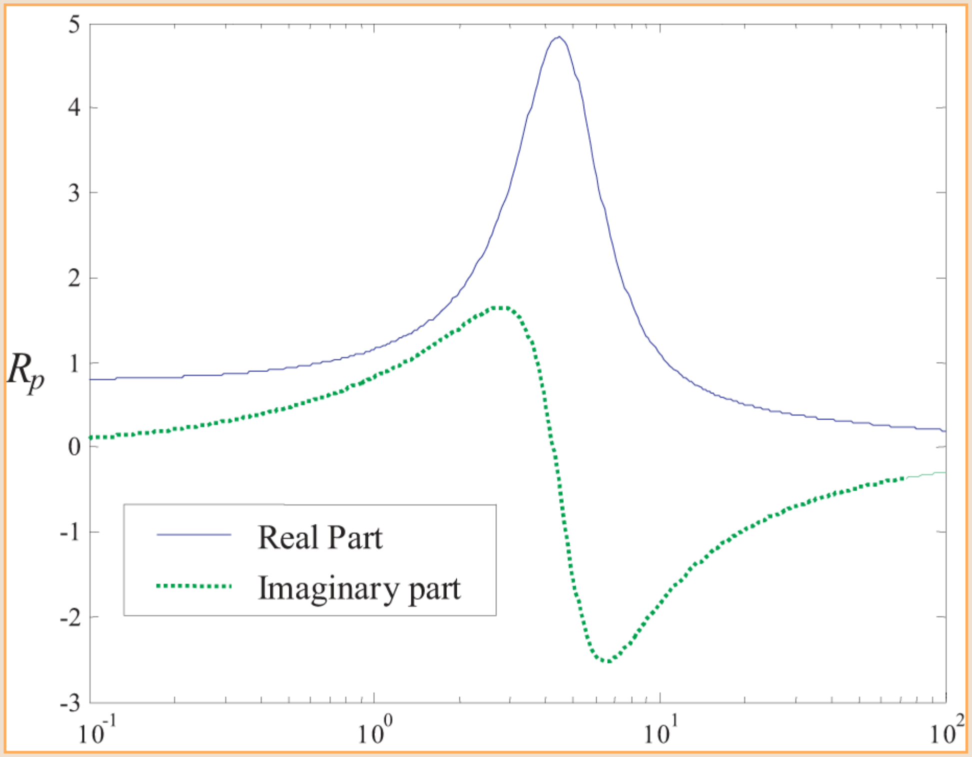




QSHOD FORMULA

$$R_p = \frac{...B = ..._s(\lambda - 1)}{\lambda + \frac{A}{\lambda} - (1 + A) + B}$$

Example of the Real and Imaginary Parts of the Response Function for the QSHOD Model



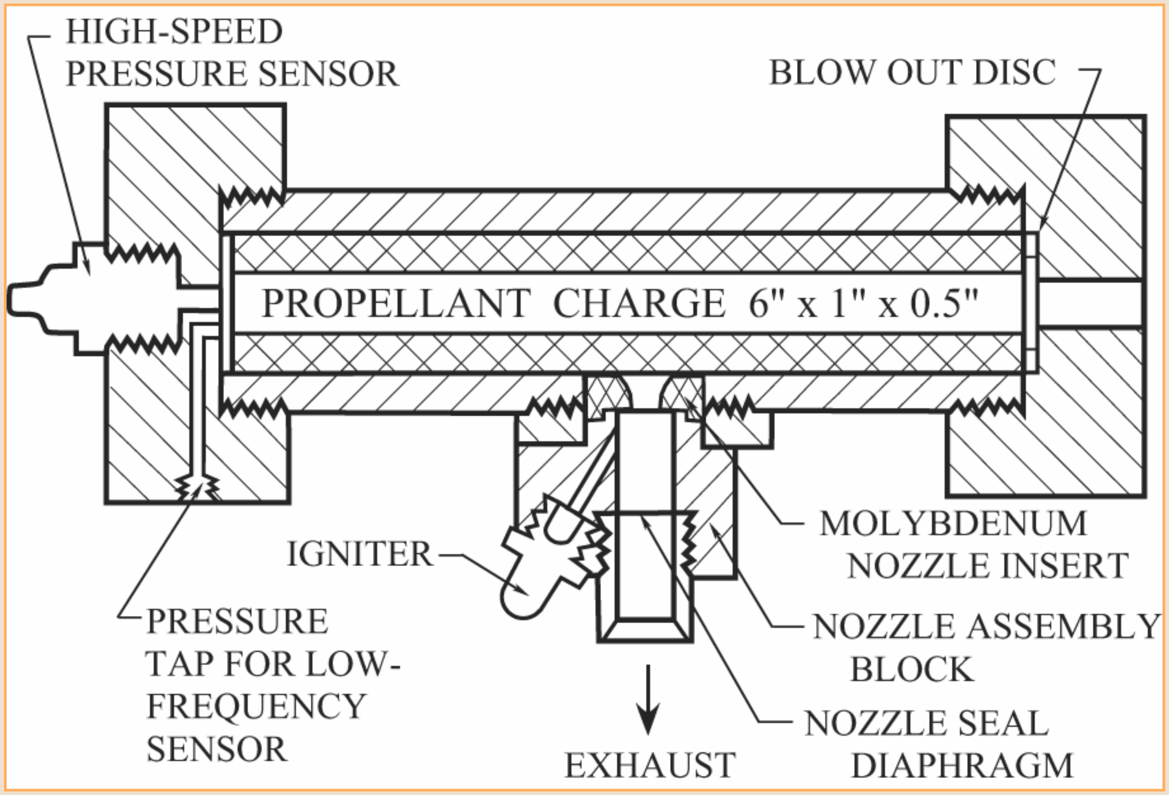
Dimensionless – Frequency

- A simple broad peak in the range of acoustic modes of motors
- Simple model easily modified to account for realistic contributions
- Real problem is obtaining realistic data for realistic propellants

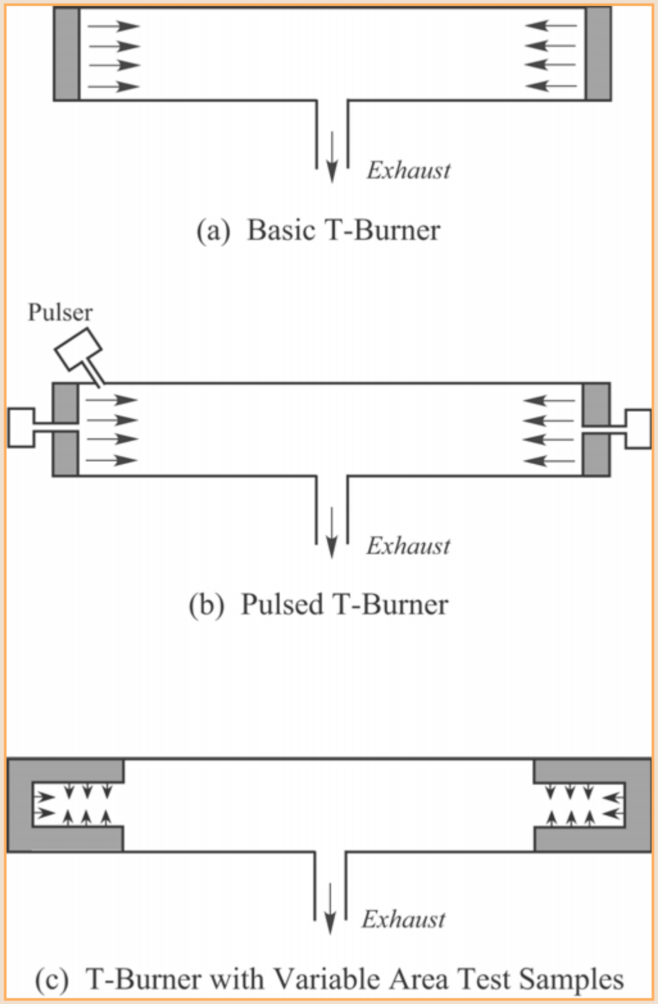
FIG. 2.23

Measurement of R_b

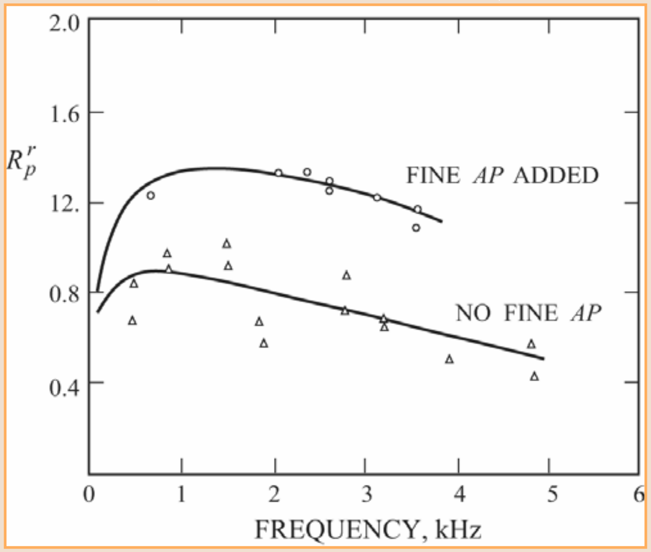
The First T-Burner
(Price and Sofferis 1958)

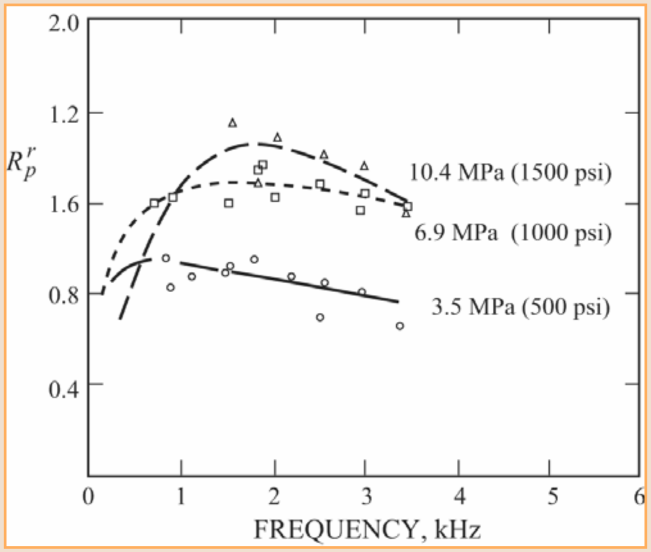


A Sketch of the Basic T-burner and Two Variants

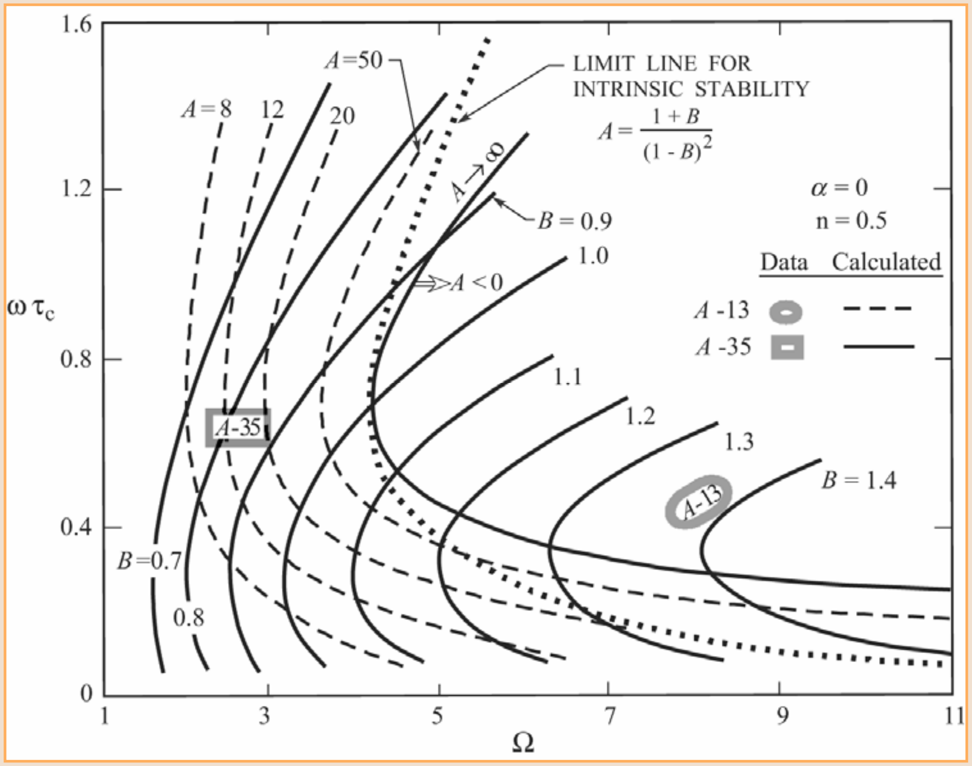


Examples of Early T-Burner Data
(Price 1984)

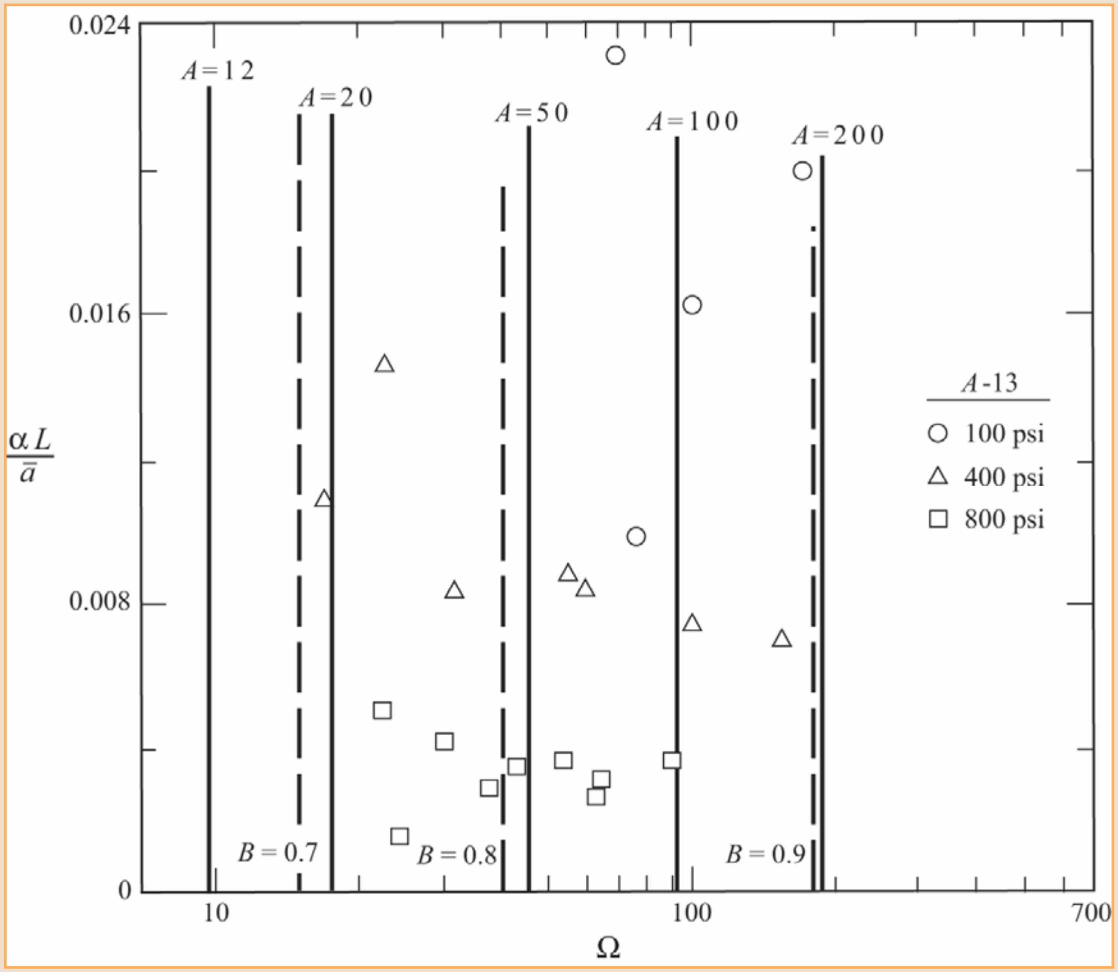




General Chart for the QSHOD Model anl L* - Burner Data (Beckstead and Culick 1971)



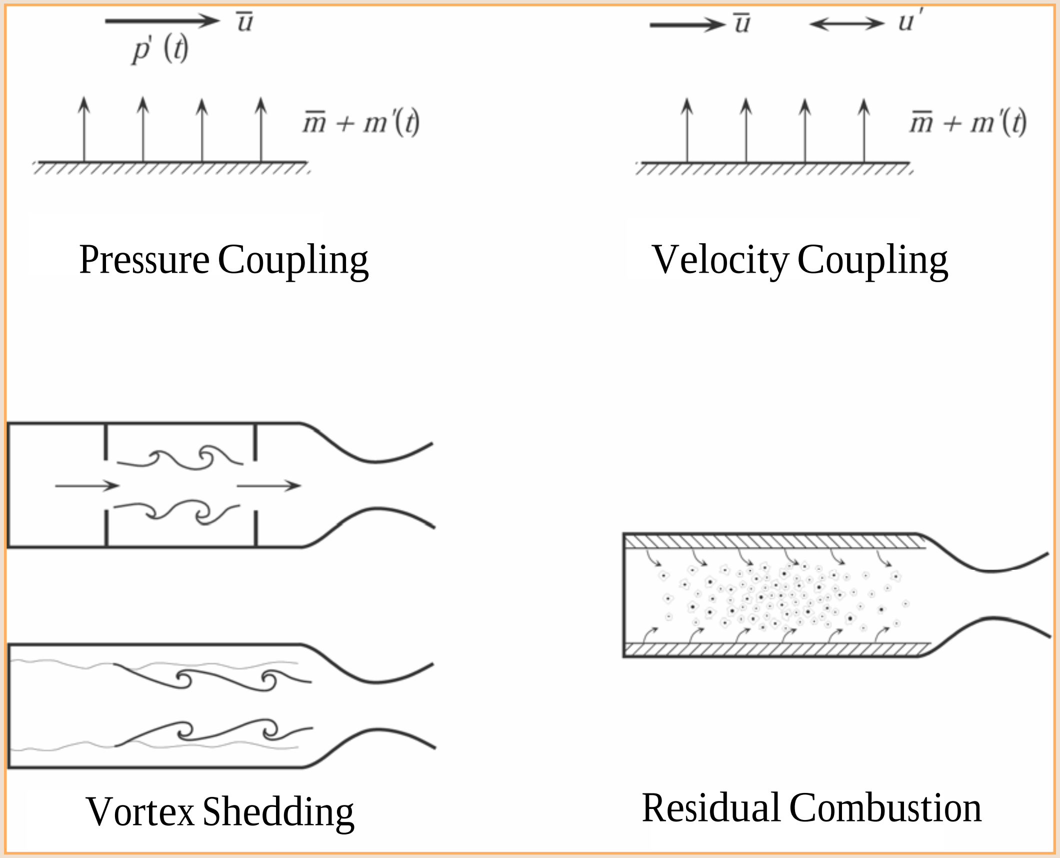
General Chart for the QSHOD Model and T-Burner Data (Beckstead and Culick 1971)



Outline

- Introduction And Background
- Some Examples
- The Primary Mechanism And Its Measurement
- The Main Mechanisms
- Passive Control
- Influences Of Noise
- Laser-based Measurement Of The Primary Mechanism
- Concluding Remarks

The Main Mechanisms



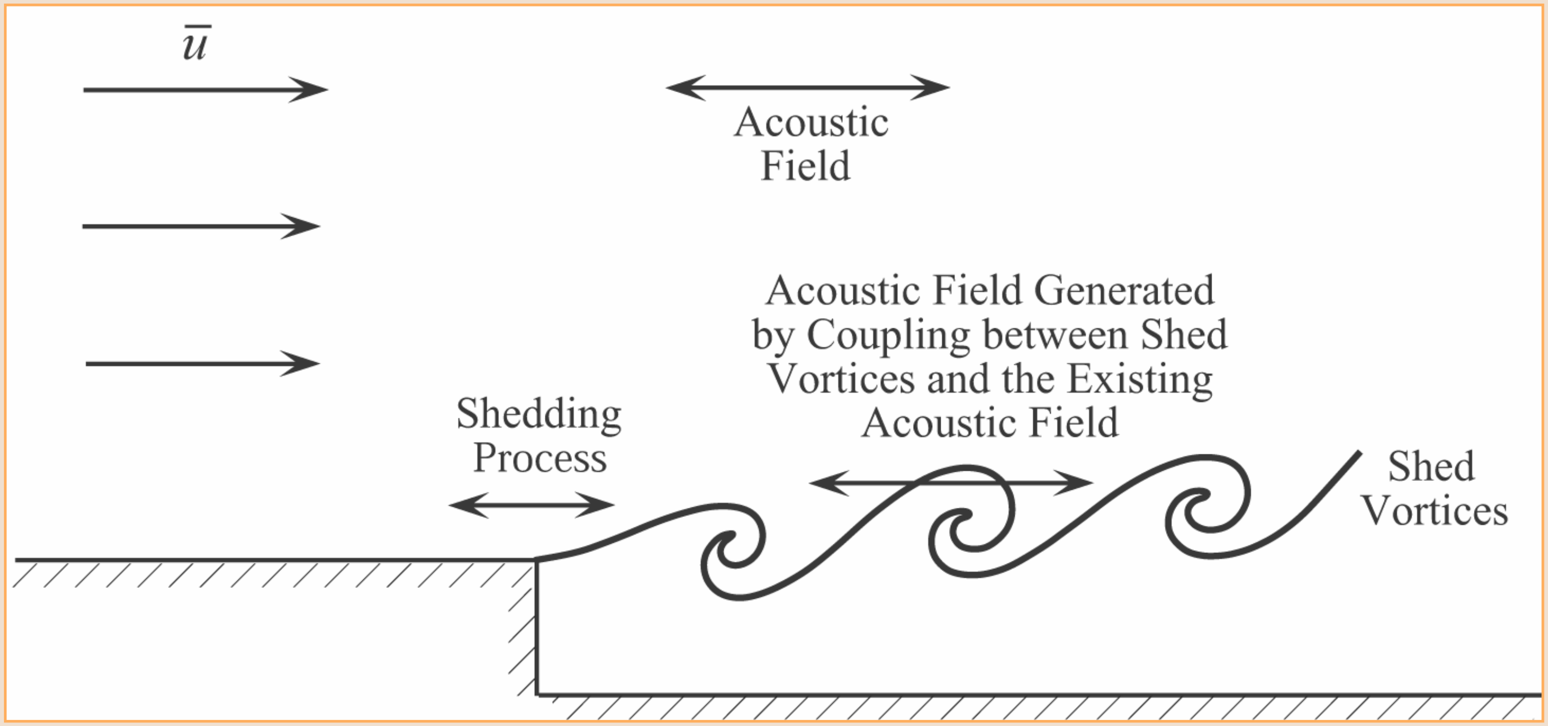
Pressure Coupling

Velocity Coupling

Vortex Shedding

Residual Combustion

Vortex Shedding at a Rearward Facing Step



Apparatus For Demonstrating The Excitation Of Acoustic Modes By Vortex Shedding (Culick And Magiawala 1979)

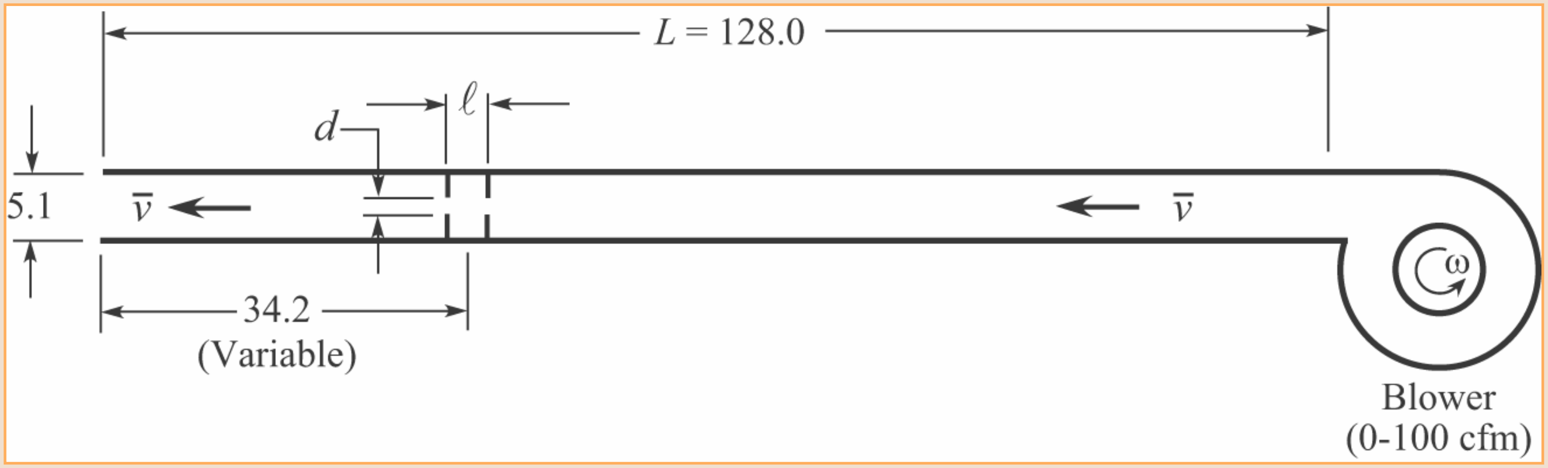
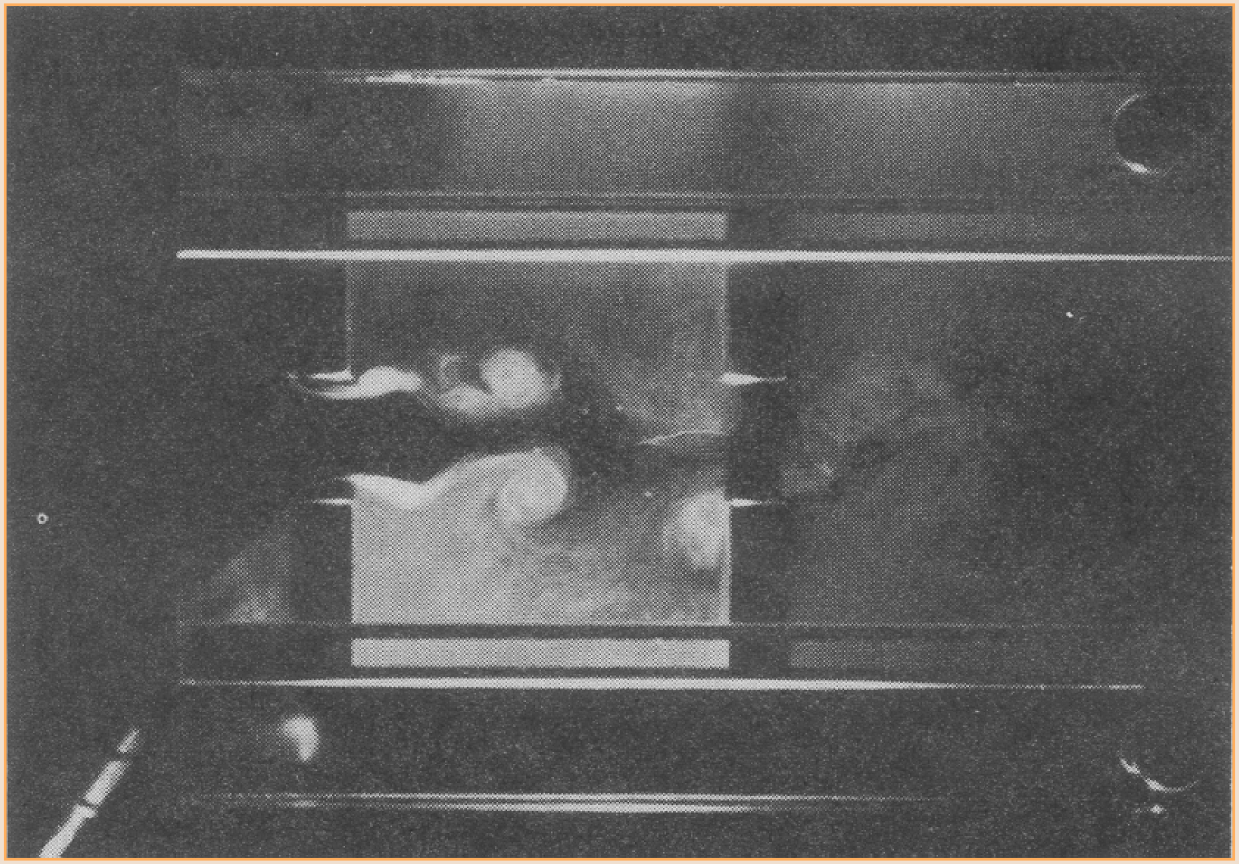
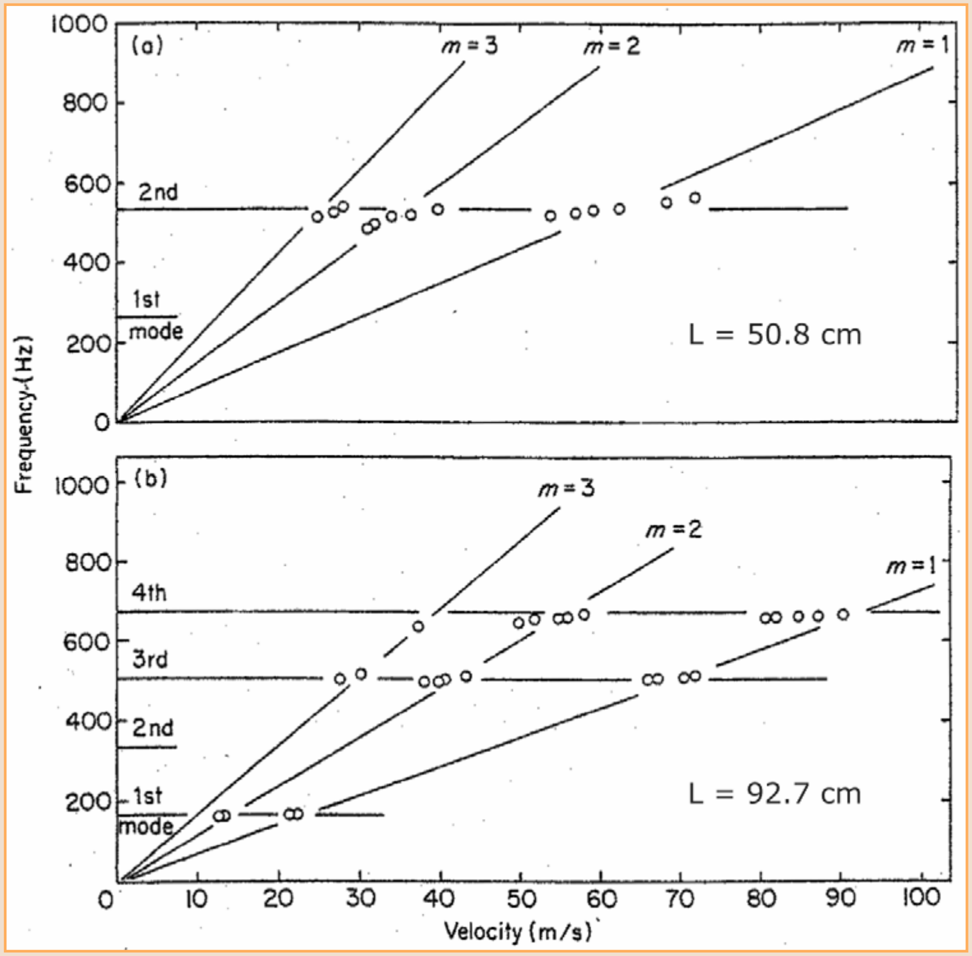


Fig 2.29?

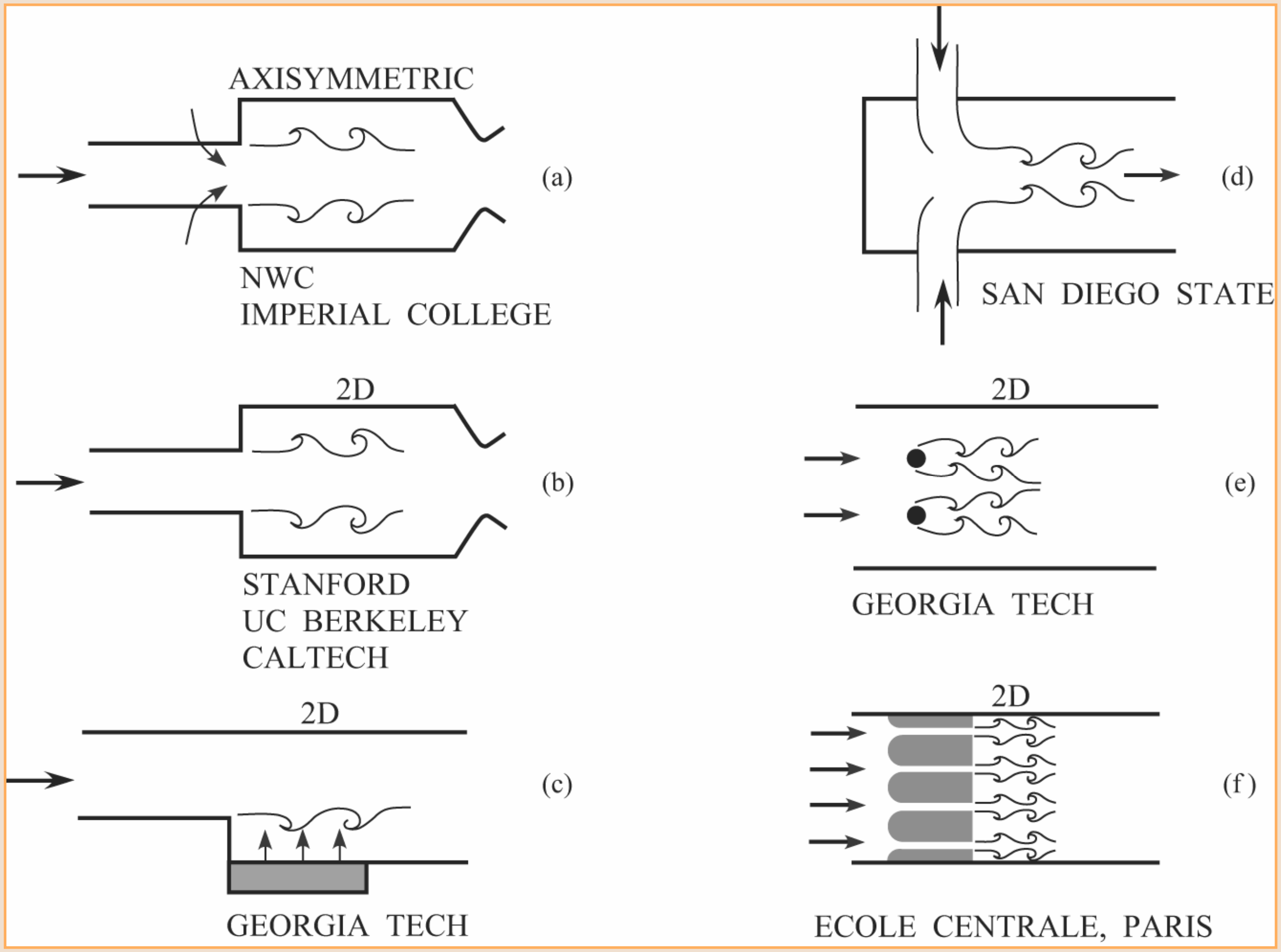
Vortex Shedding in a Simple Laboratory Device (Nomoto 1982)

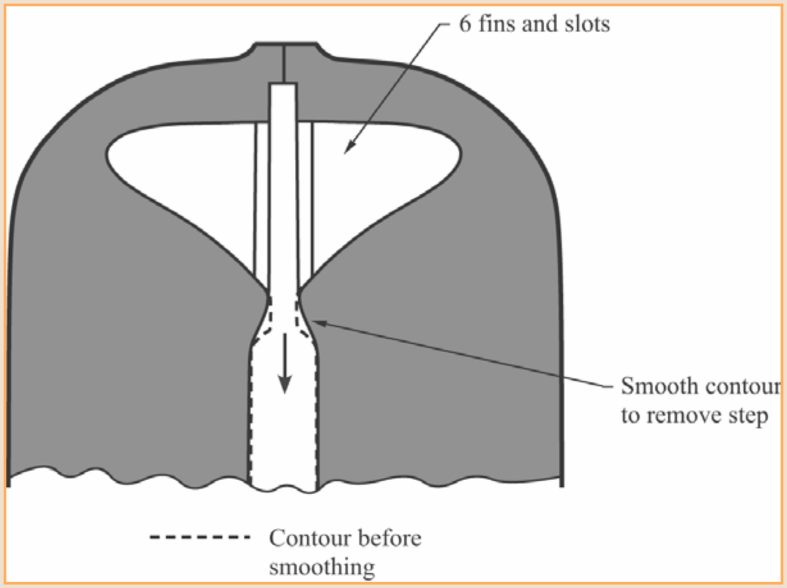


Basic Behavior Due to Vortex Shedding (Nomoto 1982)



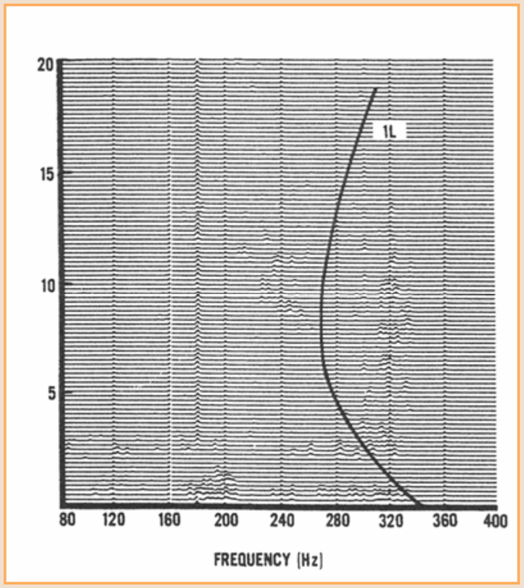
Examples of Vortex Shedding (Schadow 2001)

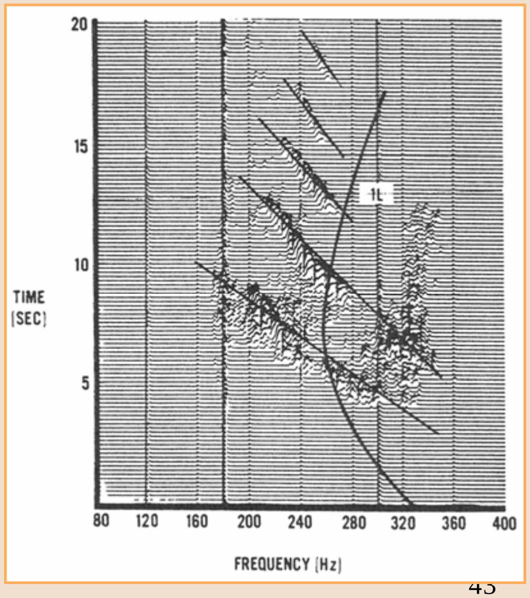




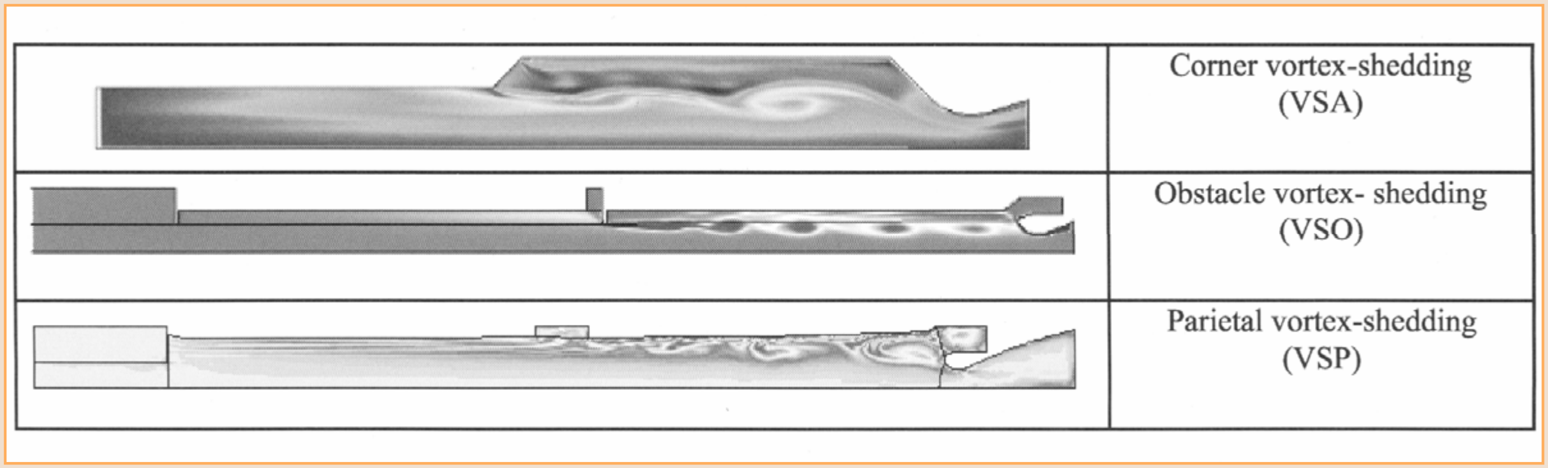
The Origin And Elimination Of Pressure Oscillations Produced By Vortex Shedding (Flandro Et Al. 1982)

'Waterfall Plots Of Low-frequency Oscillations Observed In A Minuteman III Stage 3 Motor. (Dawson Et Al. 1981)

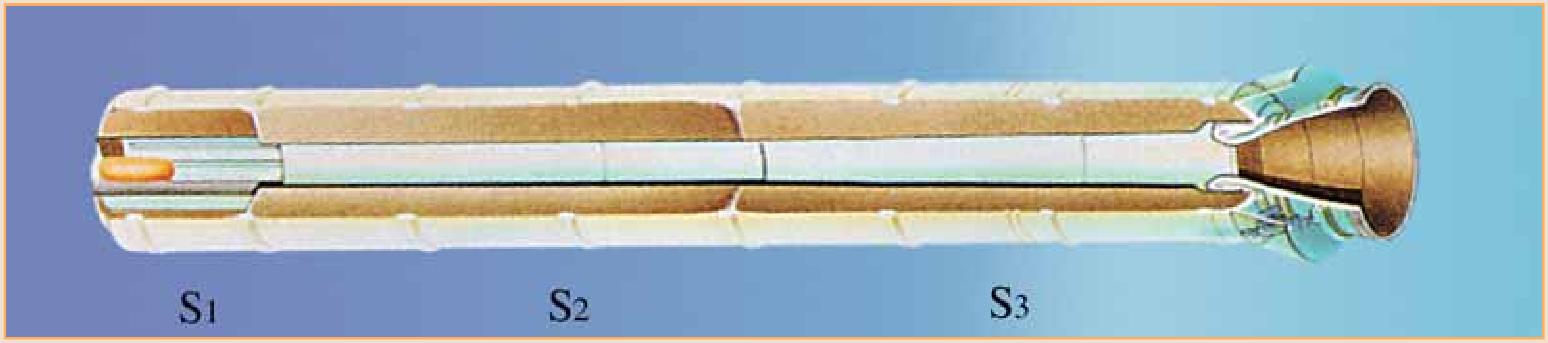




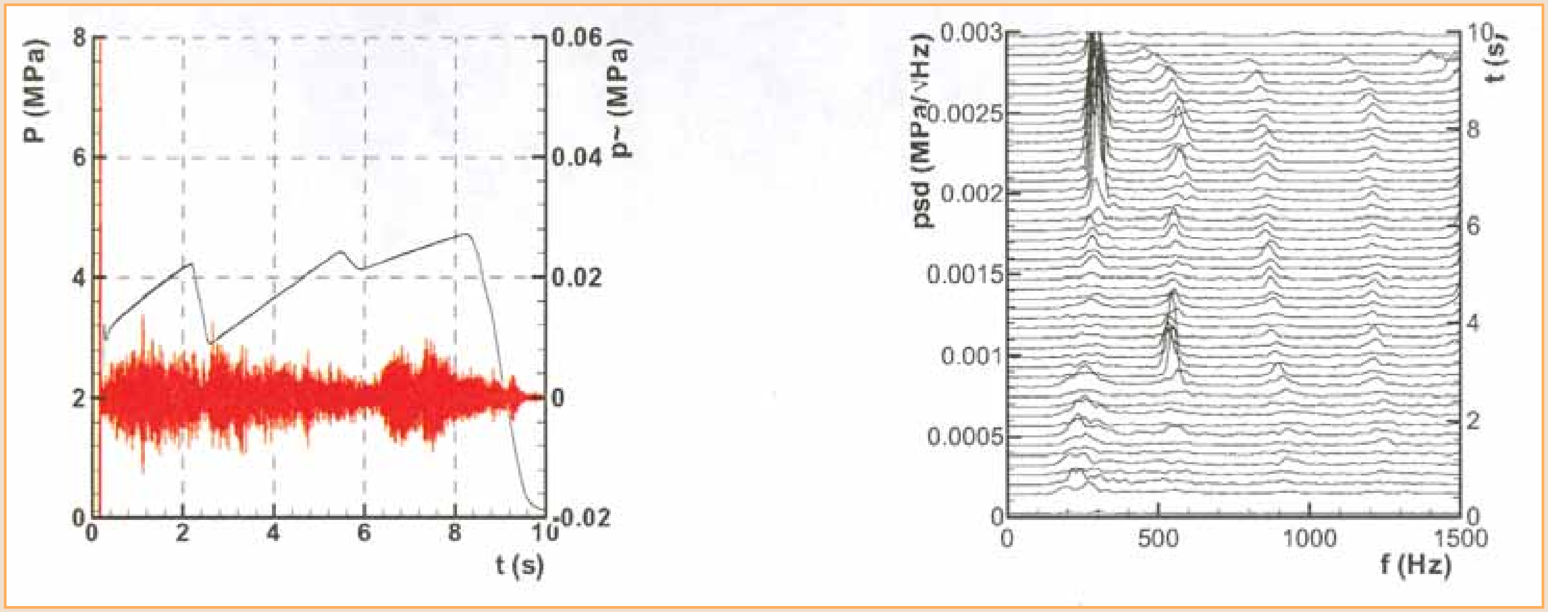
Three Basic Causes of Vortex Shedding (Fabignon et at 2003)



The Ariane 5 Booster Motor P230
(Farbignon et al 2003)

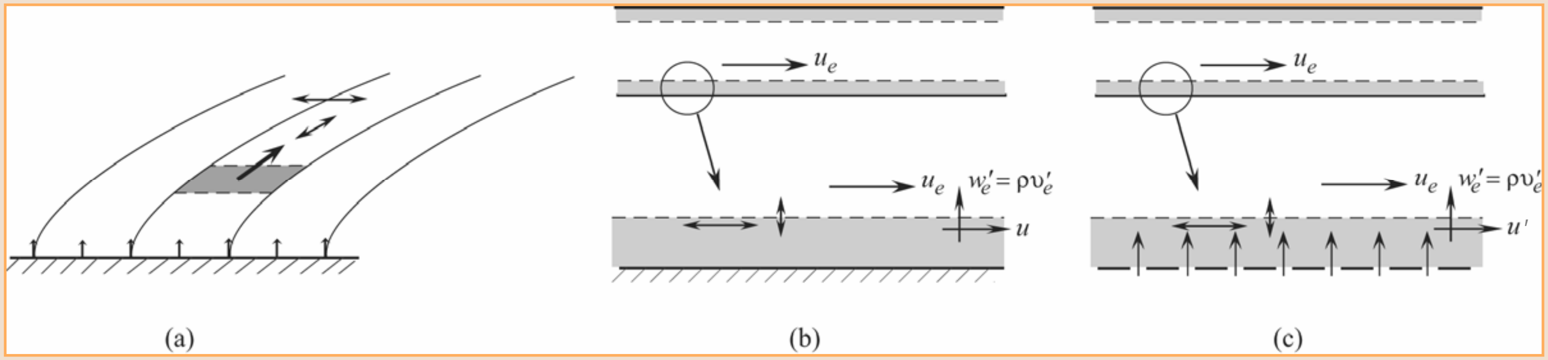


Ariane 5 Sub-scale Test Result
(Farbignon et al 2003)



Purely Fluid-Mechanical Processes at a Permeable Surface

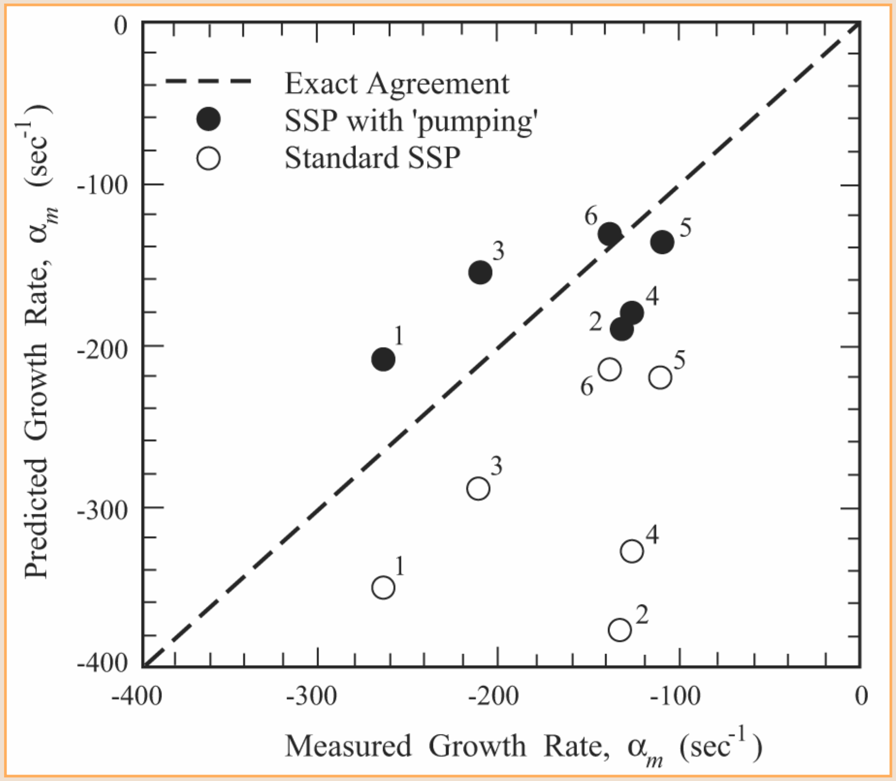
Flow Turning — Pumping



Burning Propellant — Impermeable Surface — Permeable Surface

- 'Flow turning' at a Permeable Surface
- 'Pumping' at Permeable or Impermeable Surfaces

Influence of Pumping on the Growth Rate of Oscillations (Flandro 2005)



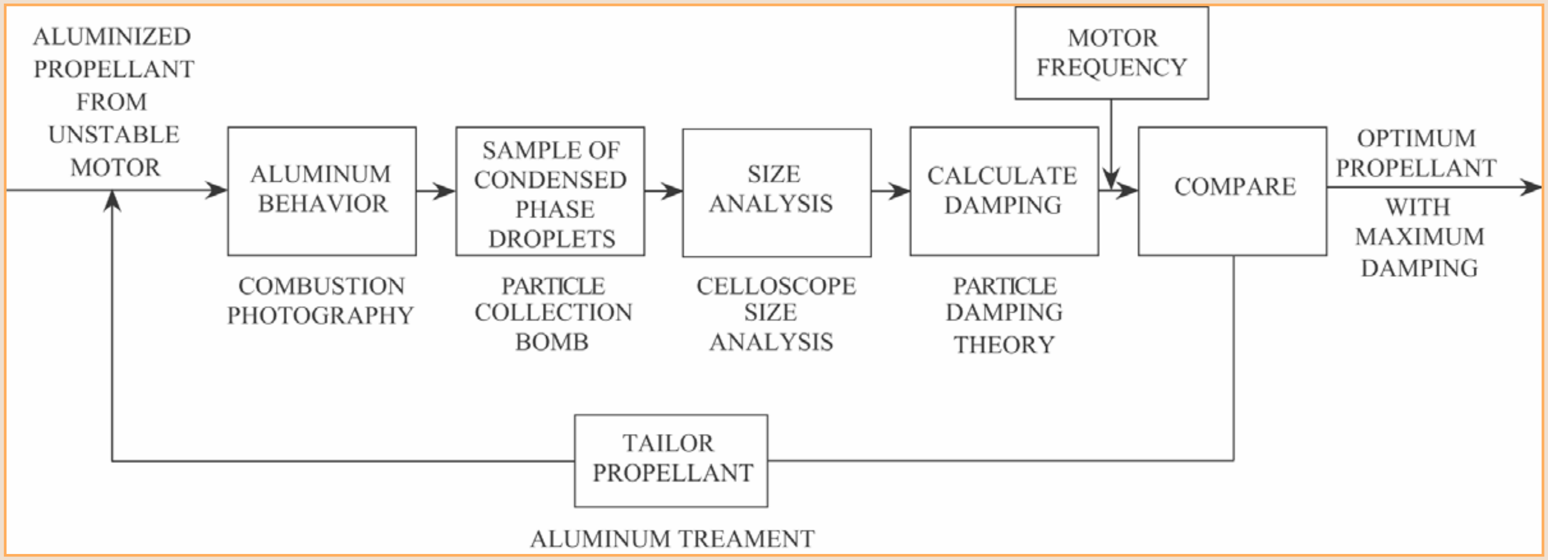
•Accounting for pumping is essential for correct assessment of burning surfaces

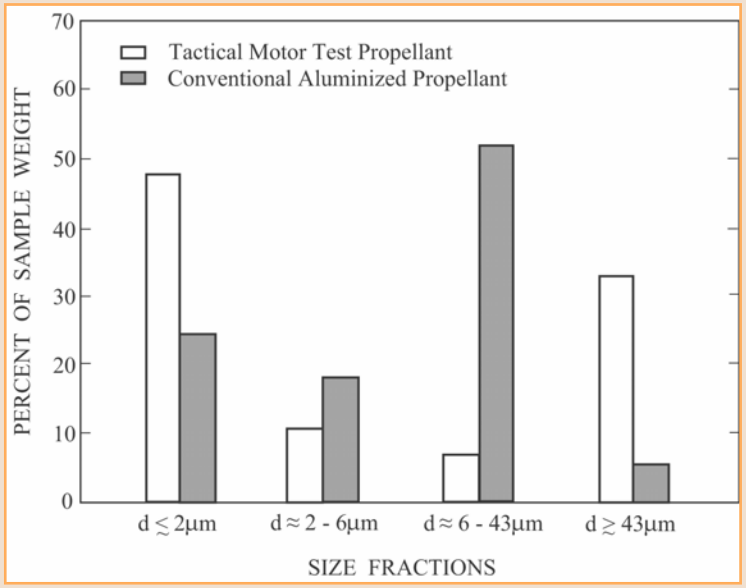
•Influence on oscillations depends on the mode shape and on the shape of the chamber

Outline

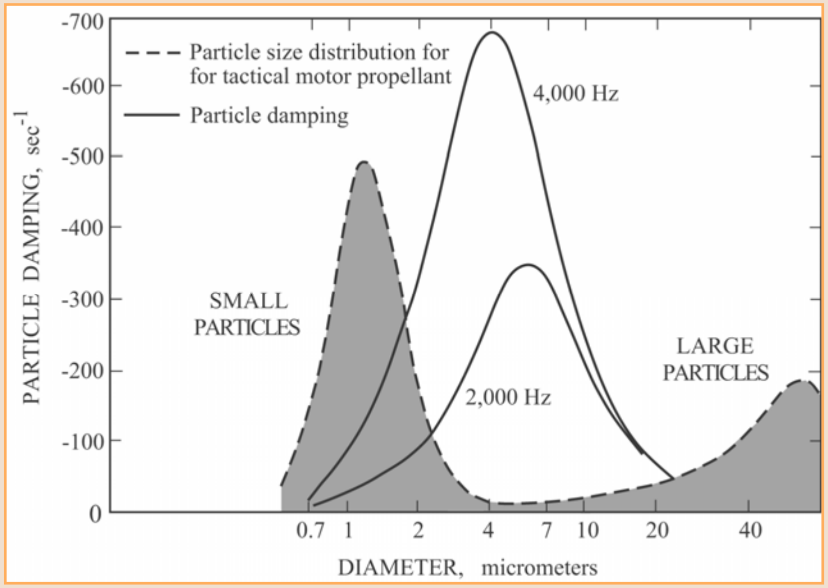
- Introduction And Background
- Some Examples
- The Primary Mechanism And Its Measurement
- The Main Mechanisms
- Passive Control
- Influences Of Noise
- Laser-based Measurement Of The Primary Mechanism
- Concluding Remarks

A Procedure To Improve The Attenuation Of Combustion Instabilities By Increasing The Particle Damping (Derr, Matthes And Crump 1979)





Particle size distributions for a tactical motor propellant and a conventional aluminized propellant (Mathes and Crump 1979)



Comparison of particle size distribution to the optimum size distribution for damping in a motor (Derr, Mathes and Crump 1979)

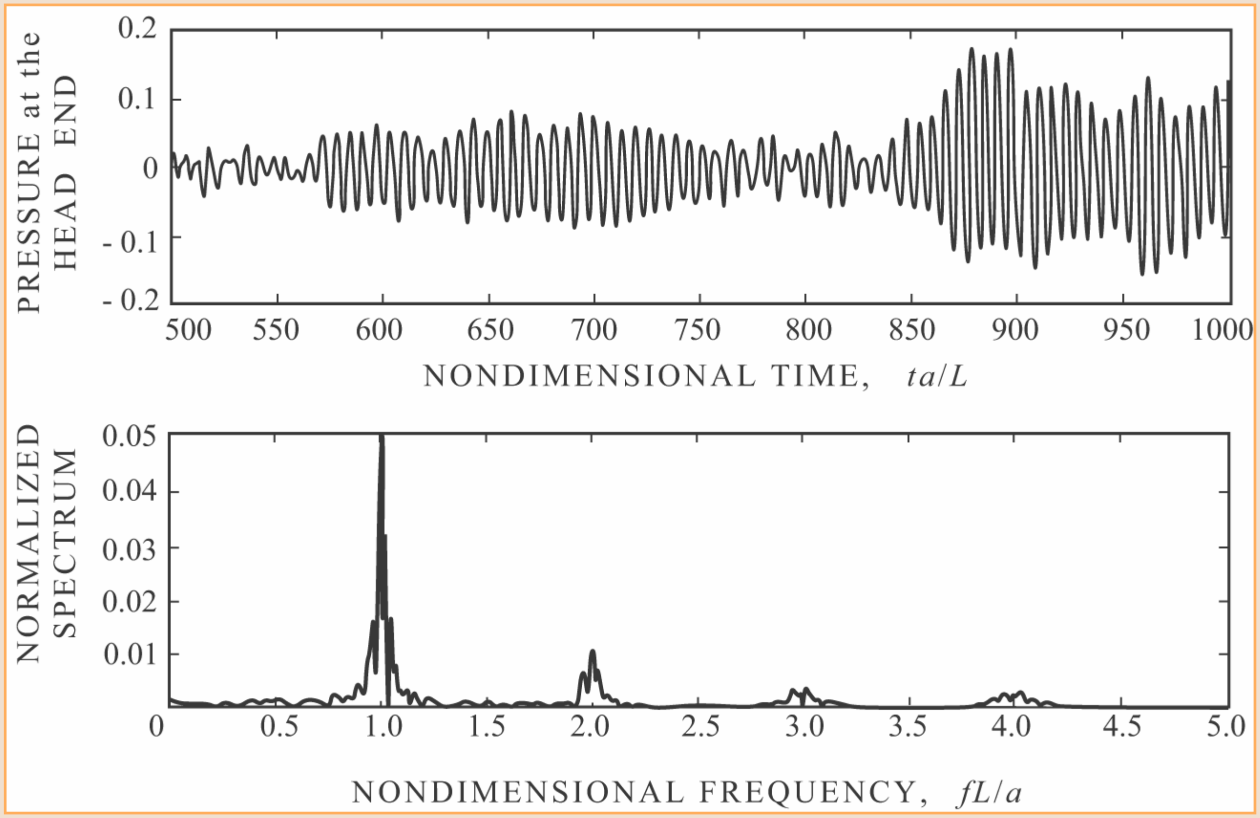
Outline

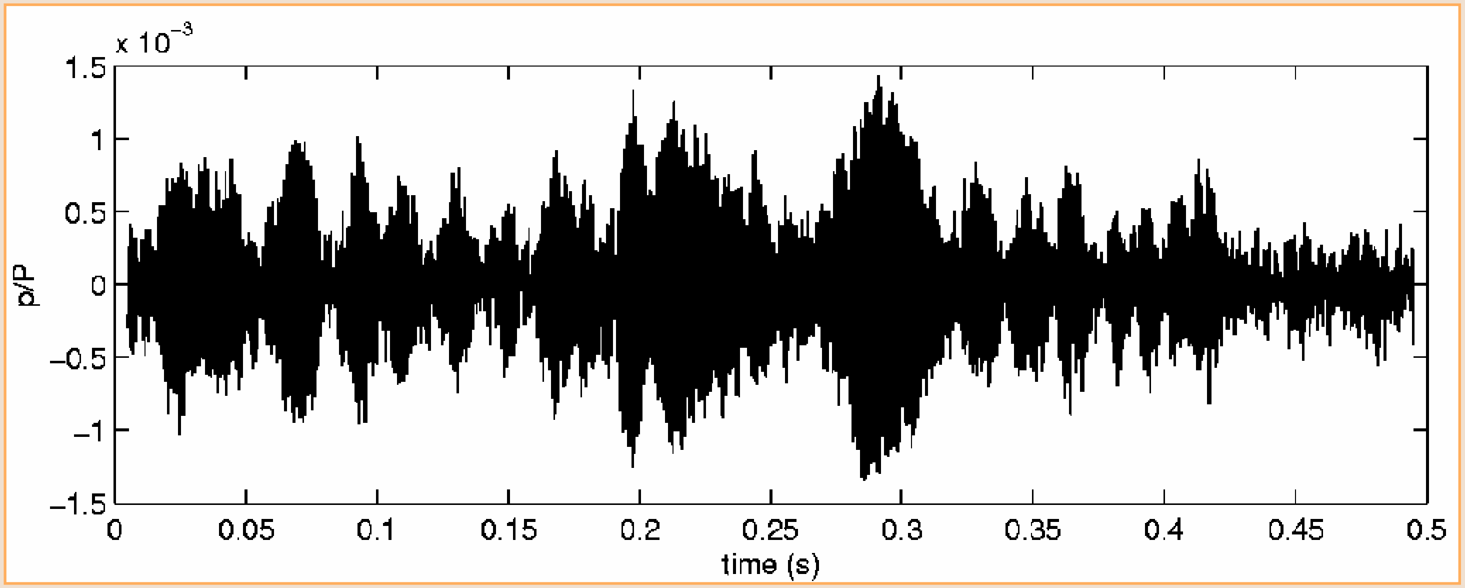
- Introduction And Background
- Some Examples
- The Primary Mechanism And Its Measurement
- The Main Mechanisms
- Passive Control
- Influences Of Noise
- Laser-based Measurement Of The Primary Mechanism
- Concluding Remarks

Outline

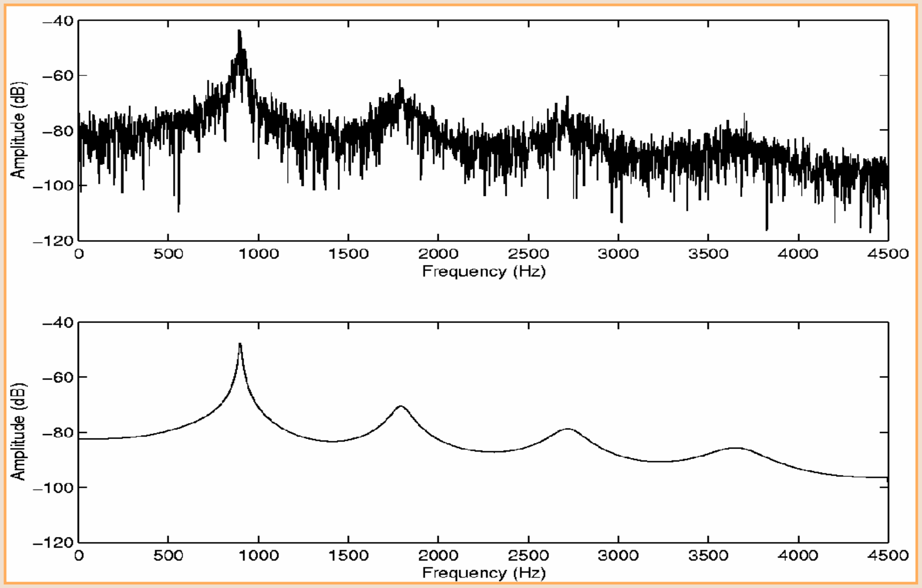
- Introduction And Background
- Some Examples
- The Primary Mechanism And Its Measurement
- The Main Mechanisms
- Passive Control
- Influences Of Noise
- Laser-based Measurement Of The Primary Mechanism
- Concluding Remarks

Pressure Trace And Spectrum For A Simulation With Noise; Four Modes Included, First Mode Unstable (Burnley And Culick 1996)

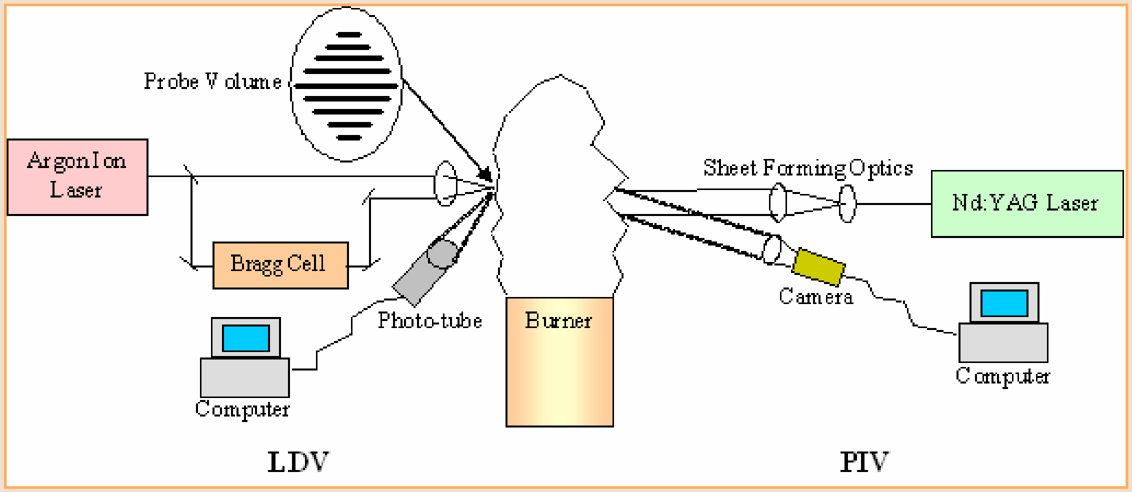




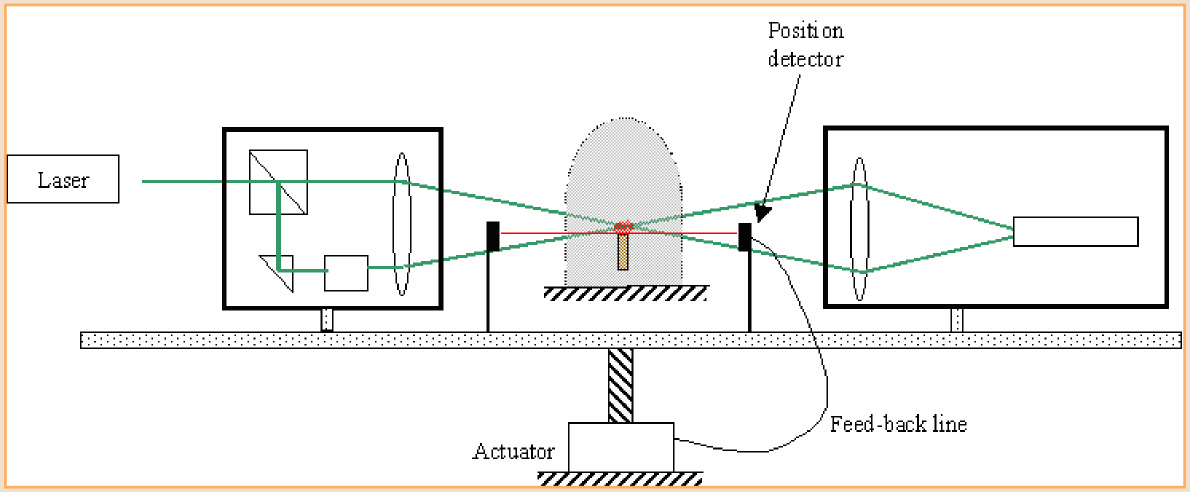
Simulated pressure trace with noise; all modes stable (Seywert and Culick 1999).



Application of Berg's method: power spectrum of the pressure trace and its reconstruction.



LDV, PIV Measurements of a Flame



Position System for...

Outline

- Introduction And Background
- Some Examples
- The Primary Mechanism And Its Measurement
- The Main Mechanisms
- Passive Control
- Influences Of Noise
- Laser-based Measurement Of The Primary Mechanism
- Concluding Remarks

Concluding Remarks

- Computational methods and power are nearly there.
  ...e.g. calculations of classical acoustic modes for 'arbitrary shapes'
- 'Complete' qualitative picture of the dominant unsteady processes with no combustion exists
  ...e.g. exhaust nozzle, particle damping, surface damping, flow-turning, pumping, fluid-mechanical processes generally
- Residual combustion is poorly understood (most recent work motivated by Ariane 5) ...
  ...questions remain concerning interactions between residual burning and particle damping
- By far, the largest and most significant 'unknowns' are the interactions between unsteady flow and a burning surface
  ...presently accurate measurements cannot be made over realistic ranges of mean pressure and frequency
  ...it is not possible to detect with small-scale tests the consequences of 'small' changes observed in full-scale fringes
- Laser-based experimental methods offer the greatest opportunities
  ...LDV, PIV, LIF, PLIF
- And that's where funding of a national facility should go