

SOME COMMENTS ON MODELING FLUID FLOW

16.540 Notes
Spring 2006

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MESSAGES

- In problems of technological interest, there are often many levels of approach possible
- There are also many levels of data that can be examined
- Not all the data is useful information
- Want to focus on those aspects that are critical to some output that we want
- We can capture many features of complex fluid flows computationally
- These high fidelity models often give more data than is needed or sometimes more than we can understand
 - Simpler (“reduced order methods”) extremely useful in extracting key points, communication, application to multidisciplinary problems (e.g, fluids, control, structures)
- This course has a focus on physical insight into fluid flow and interpretation of analysis and computation
- The course is also about being able to decide what is the level at which you need to approach a complex technological problem

A PERSPECTIVE ON 16.540

- From one perspective, this subject is about modeling complex flows
- It is thus focused not only on tools, but on methodology for developing physical insight
- The initial lecture addresses the concepts that underpin the modeling process
- What do we (Greitzer, Tan) mean by *a model*?
- Why does one want to *model*, rather than *compute*?
- What are some examples of success?
 - What flavor does this take?
- How does one go about developing models?
 - What are some guidelines for proceeding?

EVOLUTION OF ENGINEERING COMPUTATION METHODS

- A number of ideas we discuss were originally developed for computing internal flows (e.g. Secondary Flow Theory, 1-D Flow)
- These were "the" computational methods, but *in this role* they have been superseded
- As conceptual frameworks for viewing complex flows, they have *not*
- As rapid, qualitative guidelines for what is happening, as well as for insight into why it happens, they have *not*
- As a valuable aid in interpreting three-dimensional, unsteady flow computations they have assumed a *new role*; this is the context in which we view them
- During the course, we will:
 - Bring model results into comparison with computations
 - Show linkage and benefits of applying both sets of tools to problems of high technological interest.

SOME COMMENTS ON MODELING

"The art of model building is the exclusion of real but irrelevant parts of the problem, and entails hazards for the builder and reader. The builder may leave out something genuinely relevant; the reader armed with too sophisticated an experimental probe or too accurate a computation, may take literally a schematized model whose main aim is to be a demonstration of possibility. Very often such a simplified model throws more light on the real workings of nature than any number of "ab initio" calculations of individual situations, which even where correct often contain so much detail as to conceal rather than reveal reality. It can be a disadvantage rather than an advantage to be able to compute or to measure too accurately, since often what one measures or computes is irrelevant in terms of mechanics. After all, the perfect computation simply reproduces Nature, does not explain her."

--From P. W. Anderson's Nobel Lecture in Physics, 1977

SOME ADDITIONAL COMMENTS (Closer to home)

"Lord Kelvin is supposed to have stated that one only understands a phenomenon if one can calculate it; such an idea would be widely accepted now. The apparent corollary, that if one can calculate a situation one understands it, has also sometimes come to be accepted. That this is false has been amply demonstrated by three-dimensional computations of turbomachinery flows. The crucial point about the circumstances to which Kelvin was referring was that the physical situation had been simplified to the point at which the calculations could be carried out by hand or the mathematical analysis could be performed. It was the act of simplifying in order to allow the calculations to be carried out which required that the essence of the problem had been extracted"

--From N. A. Cumpsty's 1991 Minta Martin Lecture at MIT (GTL Report #213)

INTERPRETATION OF THE QUOTATIONS

- **The above two individuals address the same point**
- **Modeling, especially the conceptual process, is a key part of analysis as well as of design**
- **The question is not only what happens, but why it happens (and sometimes how it can be prevented)**
- **Understanding the mechanism in a clear way, affords the ability to do this.**
- **There is strong synergism with the use of computational methods**
- **Models are helpful as a tool in a variety of venues, from communicating results to helping guide the development of design philosophy.**

CONSIDERATIONS IN MODELING “REAL” PROBLEMS

- **Problems of high technological interest have many levels of complexity**
- **Generally want to extract enough (not too much) information**
- **Modeling extremely useful in this process**
- **Often experiment and modeling needed to move up learning curve**
- **Must have clear idea of information needed**
- **Objective (goal) should drive modeling level**
 - **“What is it that I want to know?”**
- **Examples**
 - **Tip clearance flow in turbomachinery: flow blockage and peak pressure**
 - **Rotating stall in centrifugal compressors**
 - **Combustion instability**

ENDWALL BLOCKAGE IN AXIAL COMPRESSORS

- “Blockage”, i.e., area taken up by low velocity fluid in blade passage appears to be the main limit on compressor pressure rise
- A prime cause of this blockage is the fluid near the endwall
- Can compute the flow in the blade passage, but it is difficult to extract the “reason” for peak pressure rise
- Complementary model of clearance blockage growth (Waitz, Greitzer, Cumpsty, Tan, Marble, PLUS, of course, the two students who actually did the work)
- Wanted to know how blockage scales with blade loading, inlet boundary layer, design parameters, tip clearance....
- Features of the flow that need to be captured
 - Region of low stagnation fluid
 - Pressure rise
 - Mixing
- Model tip clearance flow as a wake in a pressure gradient

COMPUTATION OF TRAJECTORY OF PARTICLES (i.e., streamlines) LEAKING OVER COMPRESSOR TIP [Furukawa et al.]

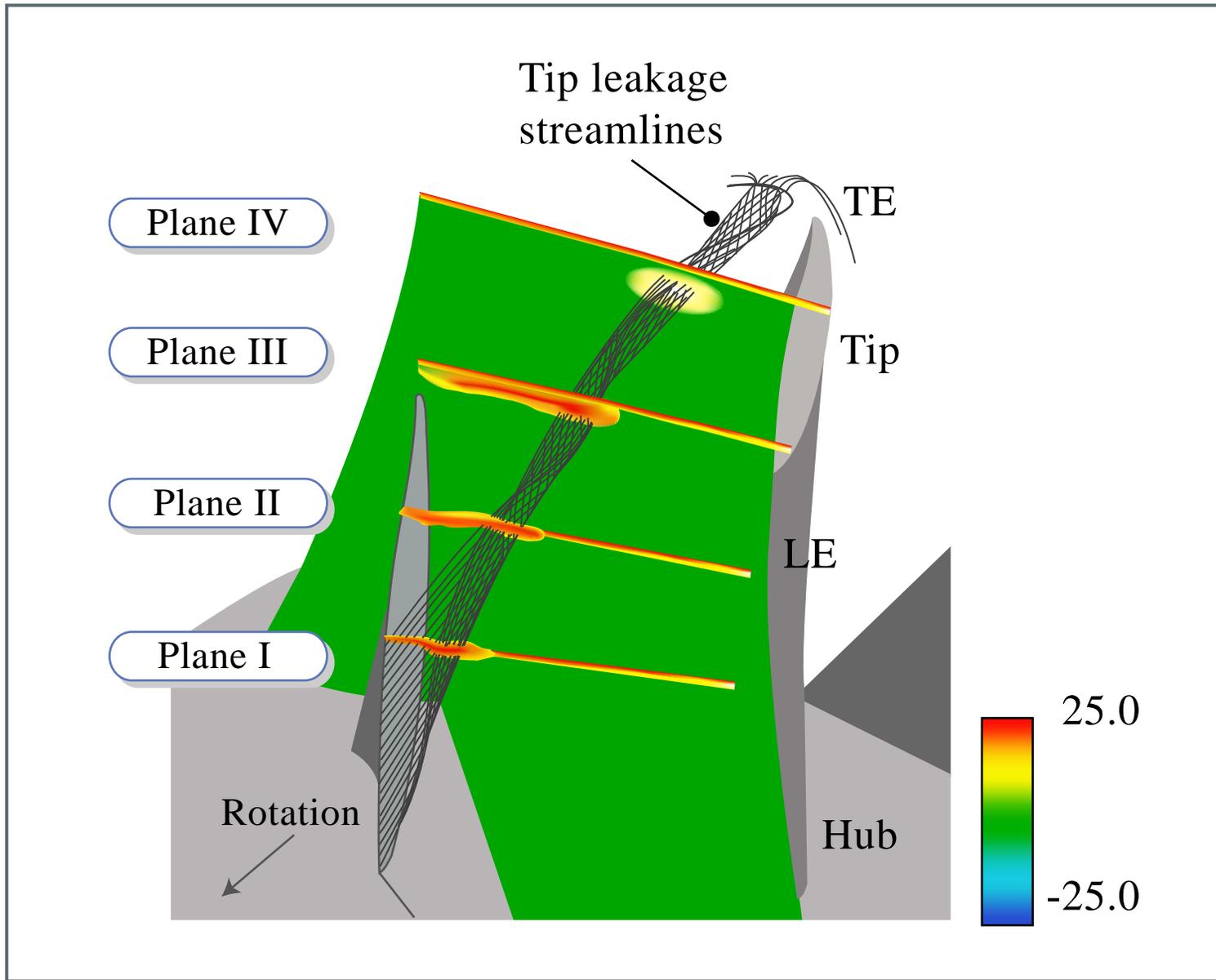


Figure by MIT OCW.

WAKE IN A STREAMWISE PRESSURE GRADIENT

- Streamtube area versus pressure rise relationship
- Response of a non-uniform flow to pressure rise
- Conditions: steady flow, $M^2 \ll 1$ (incompressible)

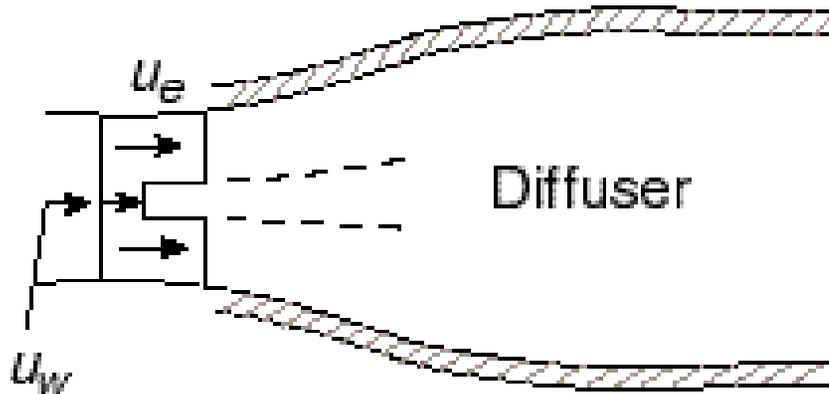
$$dp = -\rho u du \quad \text{Momentum}$$

$$d(uA) = 0 \quad \text{where } A \text{ is streamtube area}$$

$$\frac{dp}{\rho u^2} = \frac{dA}{A}$$

Increase in streamtube area \Rightarrow increase in pressure

For a non-uniform flow (wake in a pressure gradient; $\frac{U_{wake}}{U_e} < 1$)



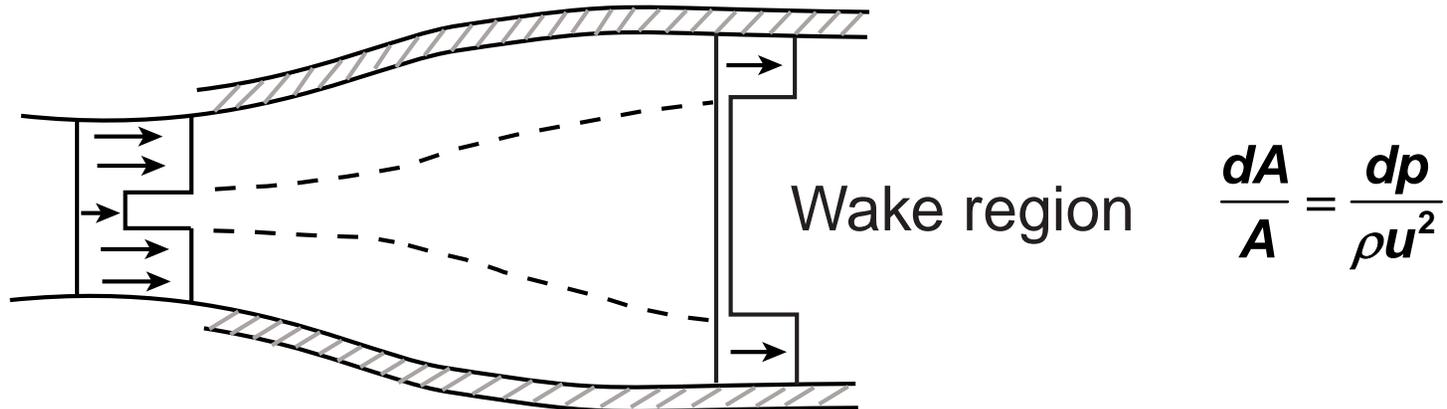
Locally, $\frac{dp}{\rho u} = -du$ is pressure rise (drop) velocity relation

dp is same for wake and freestream

u is lower in the wake

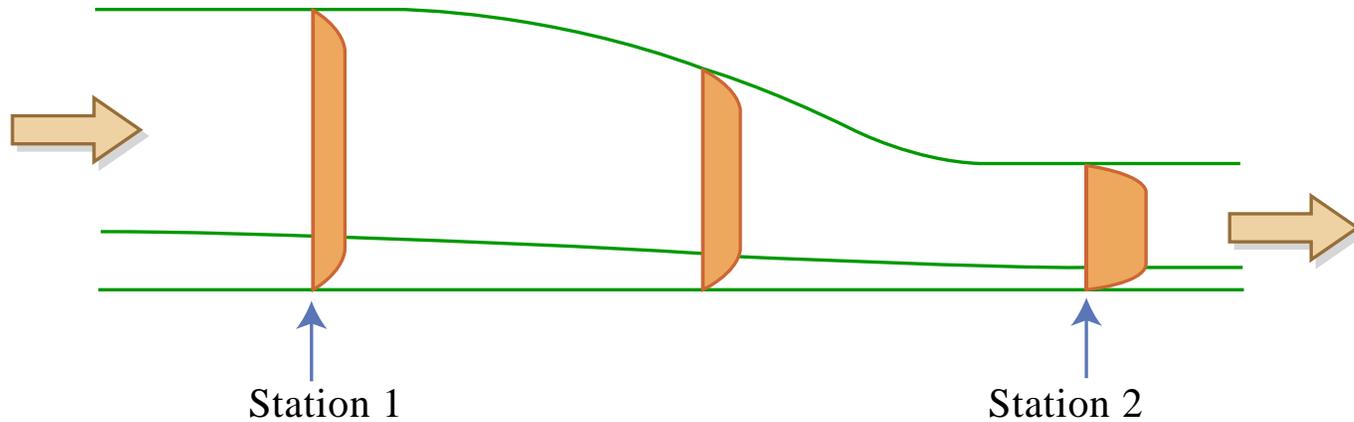
$$|du_{wake}| > |du_{wake}|$$

- Wake is decelerated more than freestream

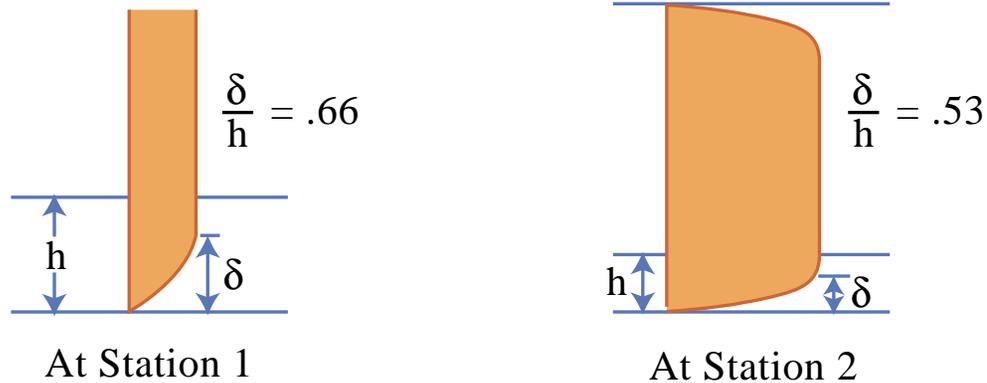


- In a favorable pressure gradient the wake (or boundary layer) is *accelerated* more and “thins out”

a



b



Flow in a 2:1 contraction;

(a) Overall velocity profiles; (b) Blowup of (a) at station 1 and 2. Hydrogen bubble flow visualization.

SIMPLE MODEL FOR BLOCKAGE GROWTH vs. CFD (Normalized by Blockage at $CP_S - CP_T = 0.6$)

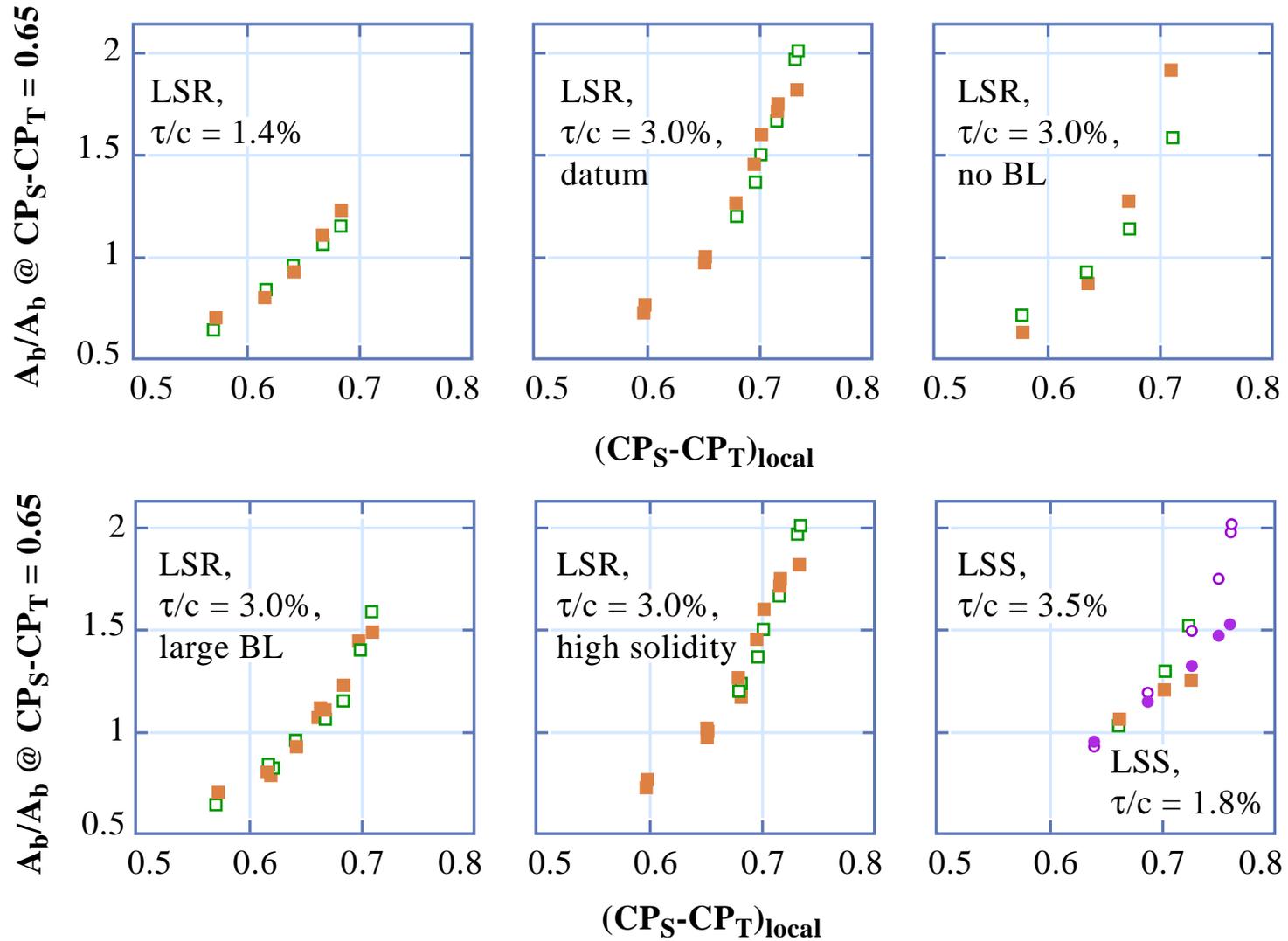


Figure by MIT OCW, after Khalid et al., ASME J. Turbomachinery, 1999.

UNSTEADY BEHAVIOR IN AN ACTIVELY CONTROLLED CENTRIFUGAL COMPRESSOR

- **Internal flow in compressor is extremely complex (3-D, unsteady, separated....)**
- **Don't need information on detailed level**
- **Needed overall information on mass flow, D_p as a function of time**
- **Used "lumped parameter" approach**
- **This provided:**
 - **Ability to examine alternative control strategies**
 - **Delineation of performance limits**
 - **Explanation of mechanism (unsteady energy flow)**
 - **Prediction of time-dependent system behavior so that model could be assessed**

LEVELS OF MODELING

- **On one level, concepts are enough**
 - **Oscillations exist**
 - **Oscillations are modes of system, control developed experimentally**
- **On another level, use simple model description**
 - **Design controller using model**
 - **Develop actuation strategies using models**
- **On a more detailed level, analyze flow within machine to determine root cause of performance**
- **Point is that there are many levels to usefully enter a technical problem--objective drives choice of level**

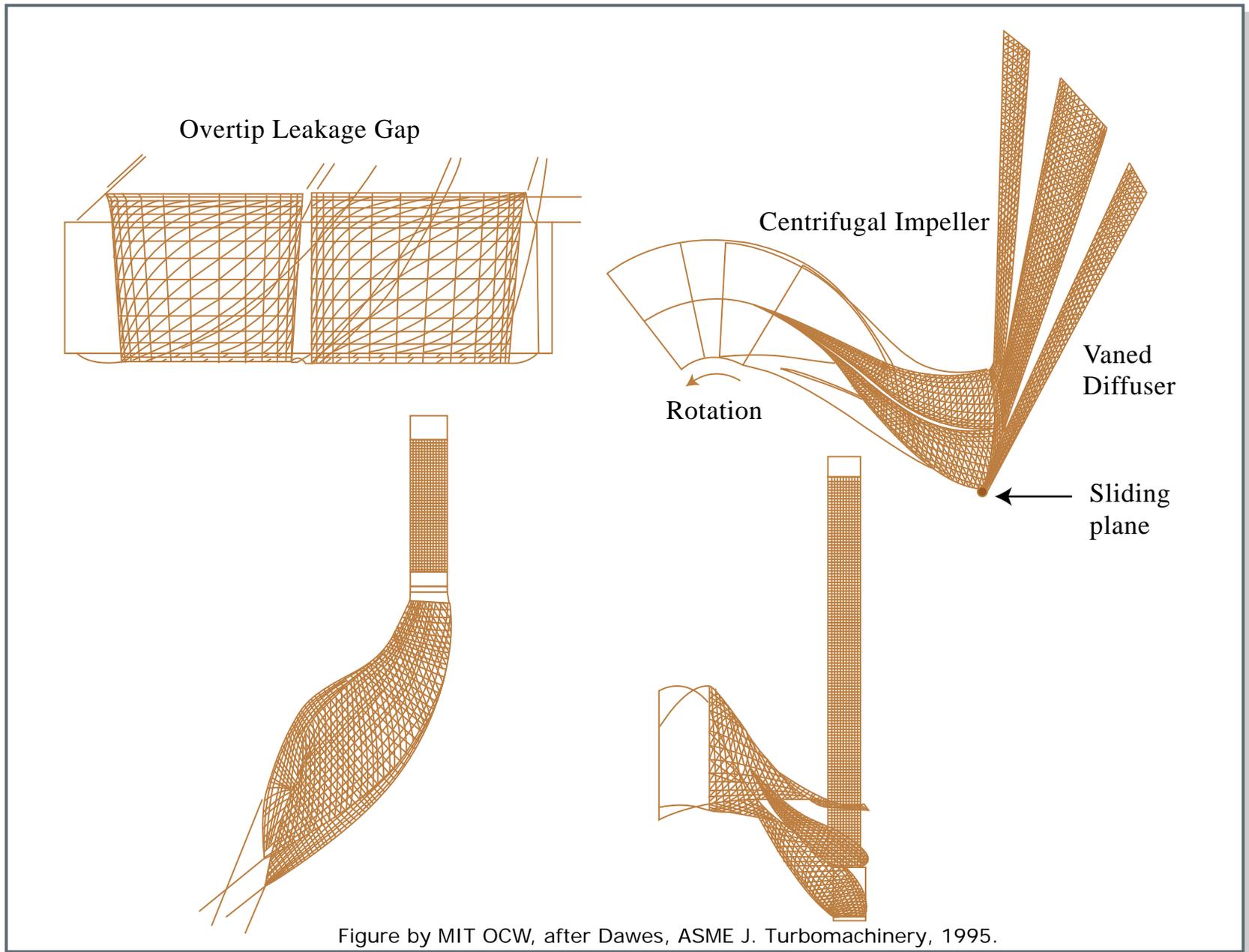
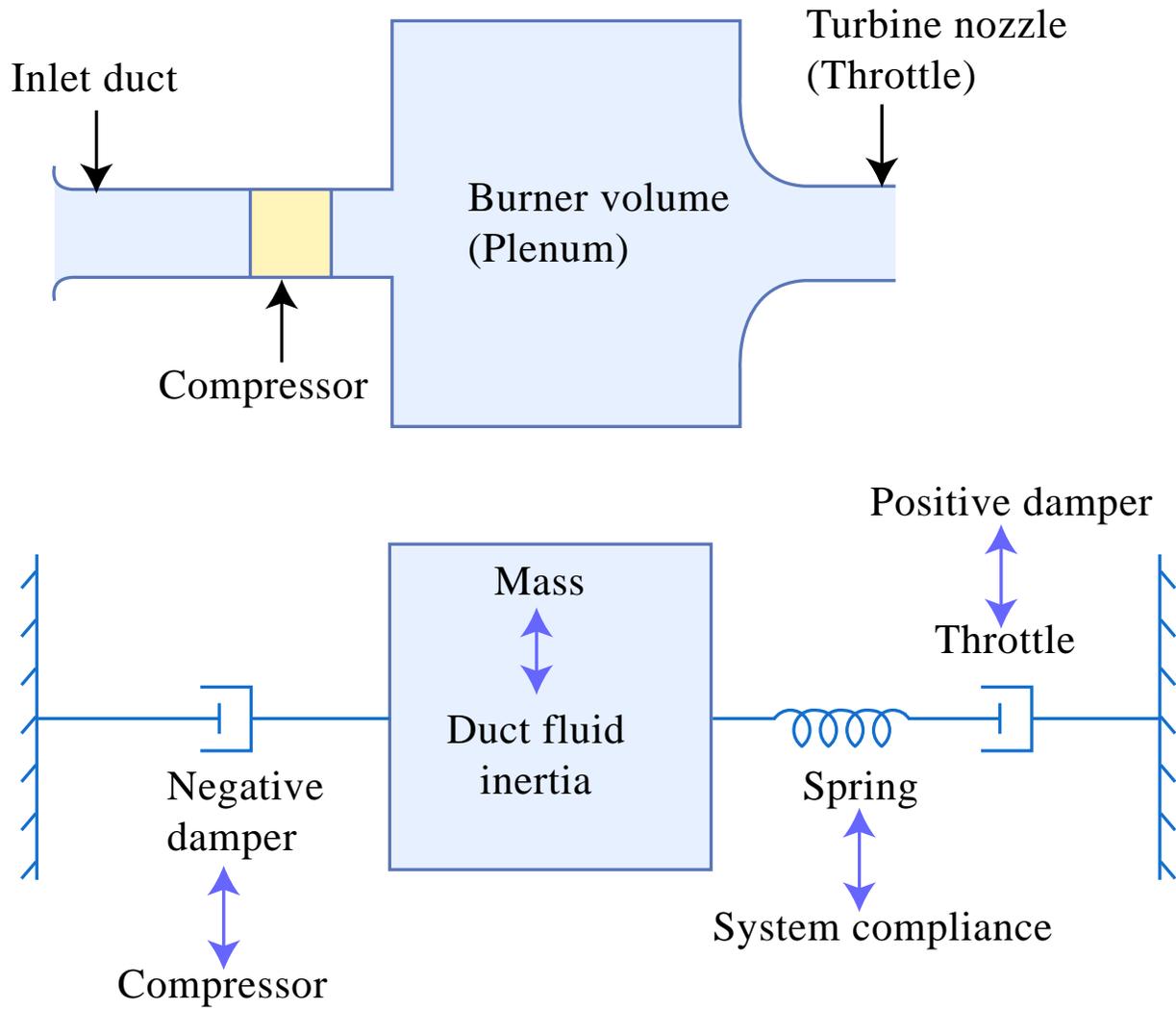


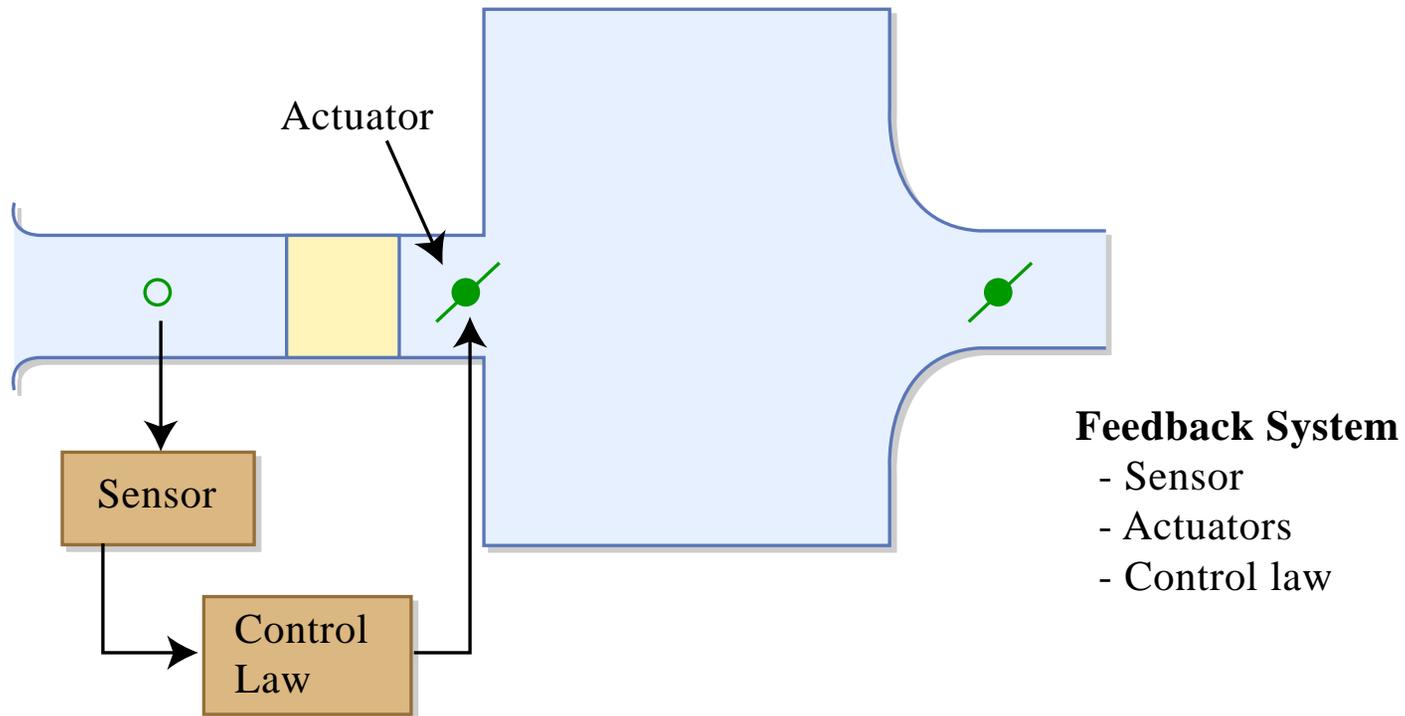
Figure by MIT OCW, after Dawes, ASME J. Turbomachinery, 1995.

Figure 6: Unstructured mesh generated for the splitter impeller.



SIMPLE MODEL CAPTURES PHYSICS

Figure by MIT OCW.



- Feedback modifies unsteady power balance
- Steady state behavior unchanged
- Many possible actuators and sensors

FEEDBACK CONTROL CAN STABILIZE SYSTEM

PREDICTED AND EXPERIMENTAL SURGE BOUNDARIES

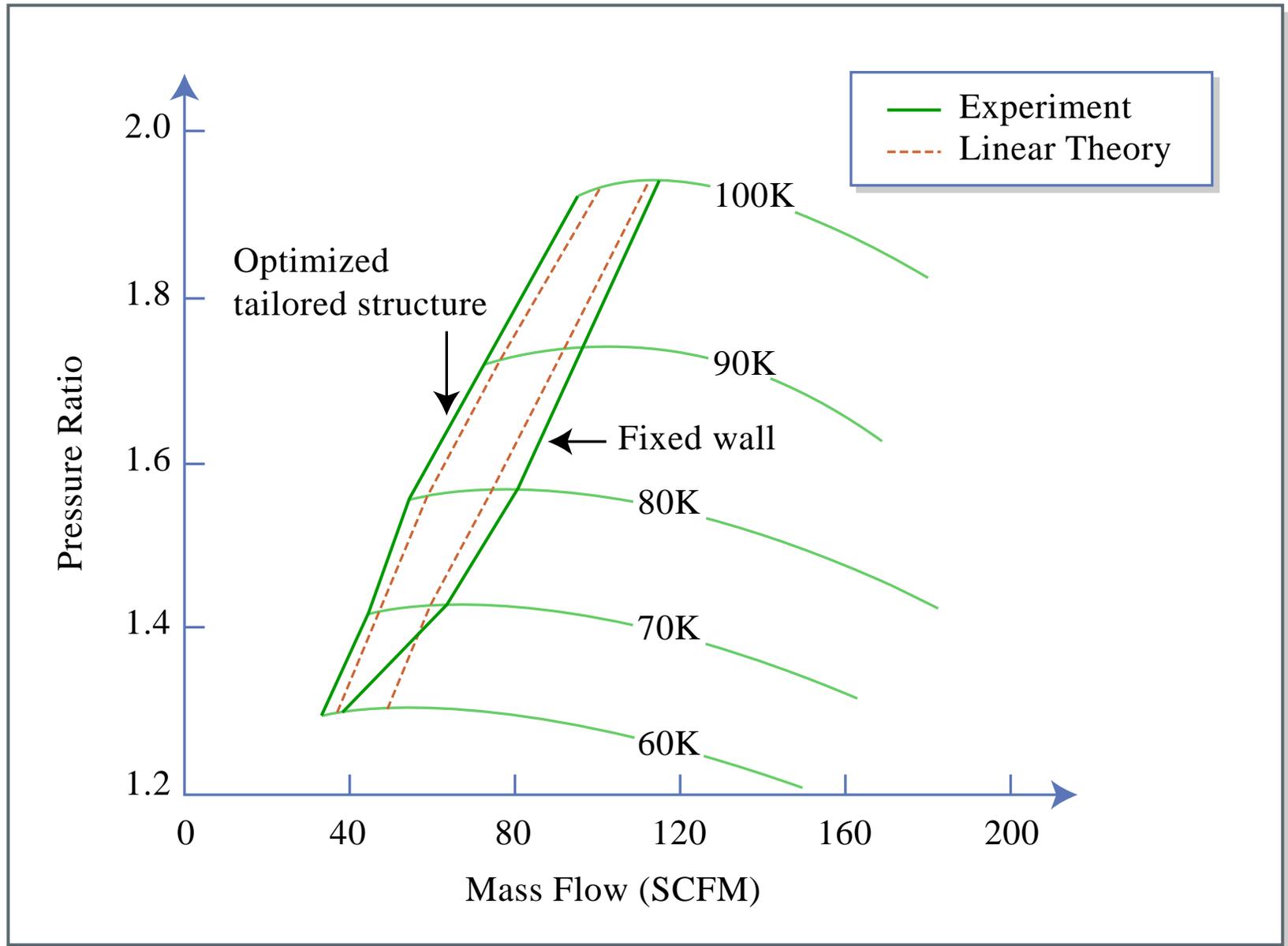


Figure by MIT OCW, after Gysling et al. ASME J. Turbomachinery, 1991.

GAS TURBINE COMBUSTION INSTABILITY

- **Energy source for instability is combustion - unsteady heat release**
- **System can be modeled by one or more “resonators” - (reminds one of compression system?)**
- **Instability can occur if unsteady heat release is in phase with unsteady pressures in combustor [Rayleigh Criterion]**
- **Possibilities for suppressing instability:**
 - **Alter phase relationship of heat release and pressure**
 - **Decrease amplitude of unsteady heat release**
 - **Augment system damping**
- **The last of these has overall energy flow reminiscent of surge control**
 - **Active element puts energy into oscillations**
 - **Damper extracts energy**

COUPLED HELMHOLTZ RESONATOR MODEL OF COMBUSTOR (UTRC)

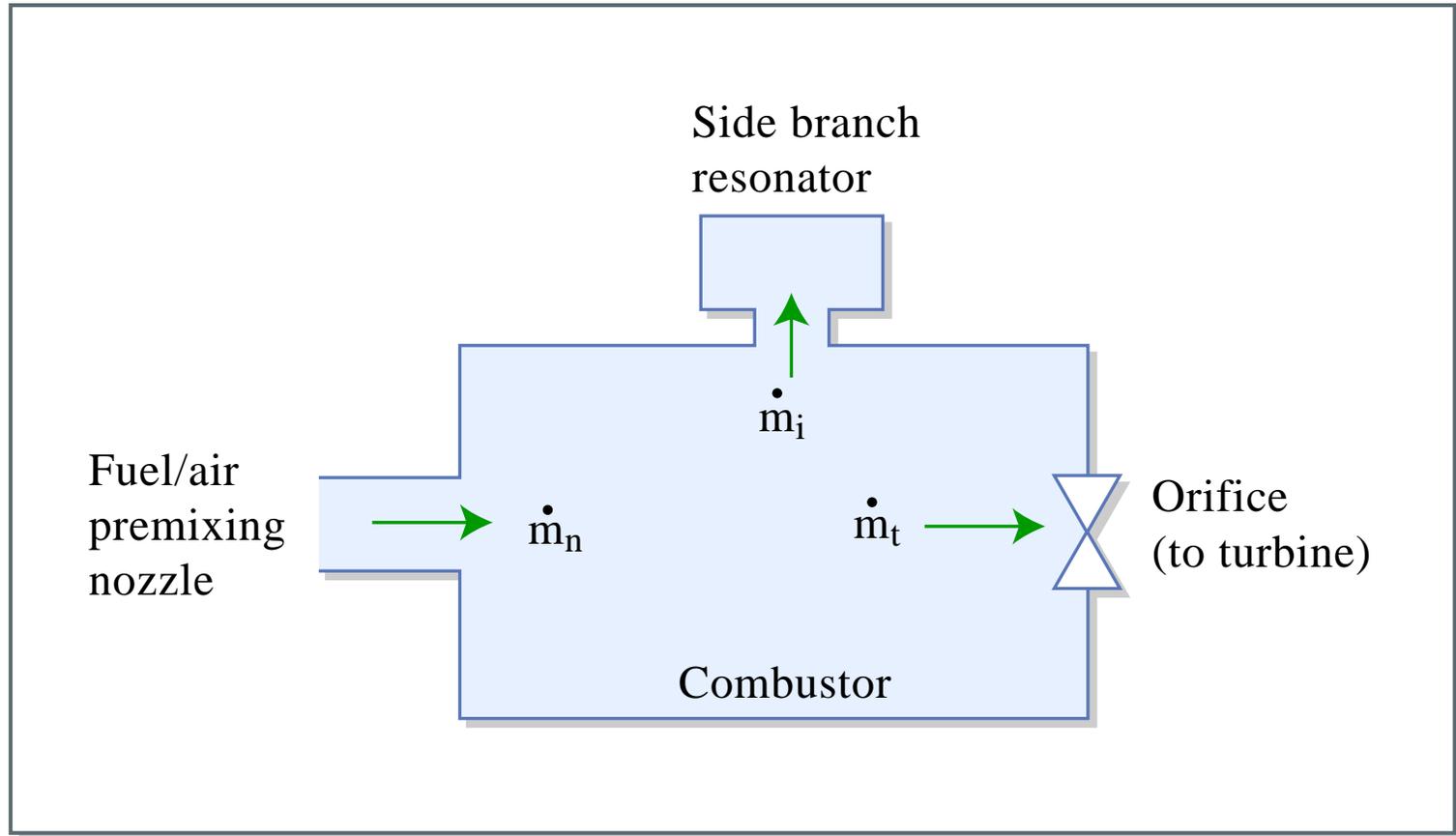


Figure by MIT OCW, after Gysling, Copeland, McCormick, Proscia, 1998.

APPROACH TO DAMPING AUGMENTATION

- **Simple model (see above)**
- **System identification to define model parameters**
- **Damping added through side-branch resonators**
- **Coupled model/experimental studies provided design trends**
- **Throughout process, need understanding of system dynamics**
 - **Frequency mismatch as power changes**
 - **Effect of resonator volume on damping**

DAMPING AUGMENTATION CALCULATIONS

Three Resonator Configurations, Combustion System At Two Power Levels; Combustion System And Sidebranch Resonator Parameters Identified From Experiment

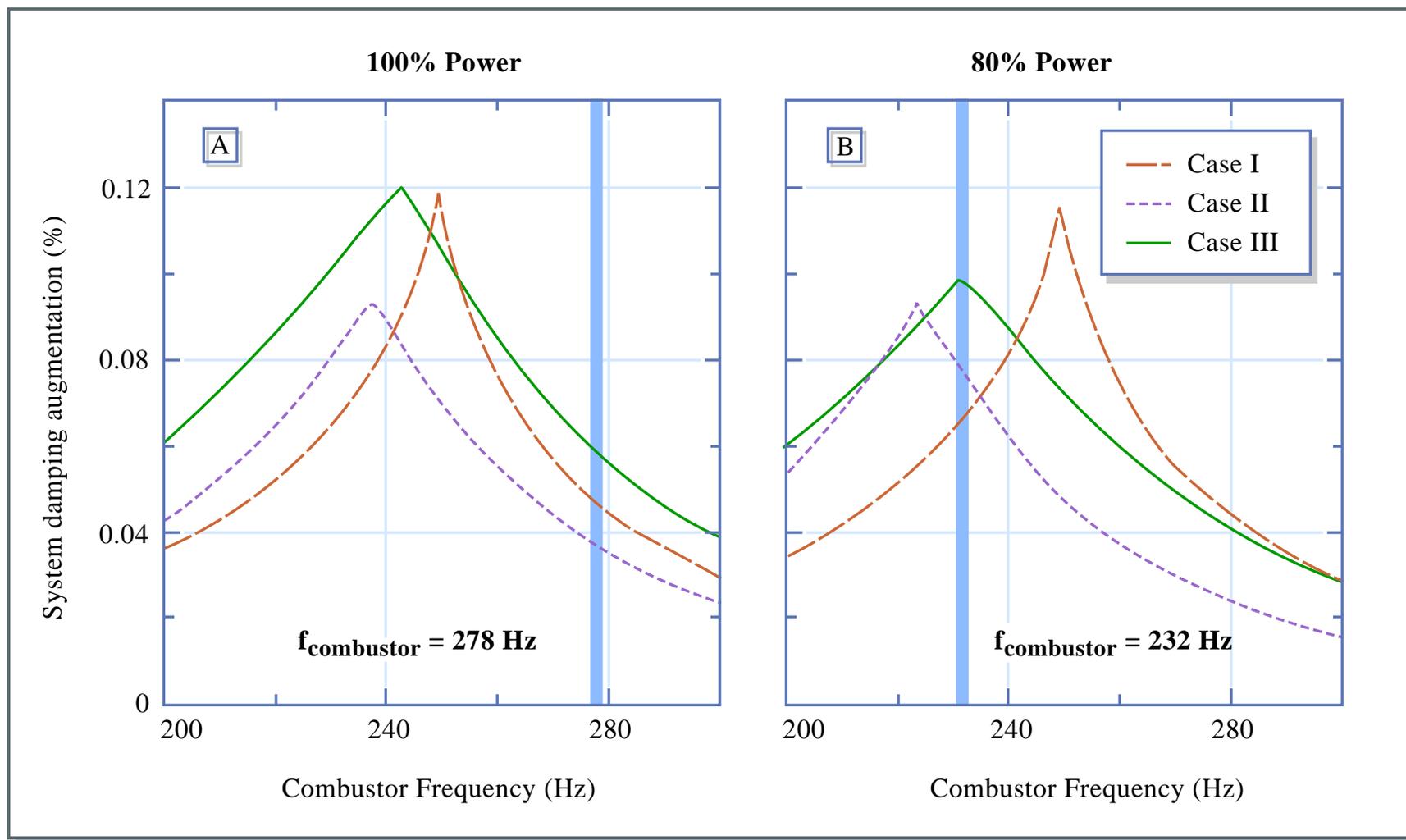


Figure by MIT OCW, after Gysling, Copeland, McCormick, Proscia, 1998.

SOME MODELING GUIDELINES

- **Define use to which a simplified model will be put**
 - **Helping to interpret CFD**
 - **Providing rapid (approximate) design aid**
 - **Communicating results to technical audience or management**
- **Define phenomena you think need to be captured/questions to be answered**
 - **Example: tip clearance flow in turbomachines mainly pressure-driven, dominated by inviscid considerations**
 - **To understand parametric behavior does one need to worry about turbulence modeling?**
- **Define level of fidelity/accuracy needed**
- **Clearly define approximations being made**
- **Define predictions model will be able to provide**
 - **Are these consistent with the original objective?**
- **Set up differential equations (integral forms) which are the mathematical statements of the model and solve**
- **Examine results for consistency (Are approximations valid?)**

SUMMARY (FOR NOW!) ON MODELING

- **Modeling (as defined here) spans a range of levels of complexity**
- **No “one size fits all”**
- **Provides a complement to detailed computations**
- **The line between modeling and computation is a blurry one in terms of complexity**
 - **Computationally intensive model, simple computation**
- **The conceptual difference, however, is clearer**
- **The objective is to capture the important physical effects in a manner that serves to clarify the overall problem**
- **To paraphrase Albert Einstein, the model should be as simple as possible, *but not simpler.***