Design optimisation of a clarinet

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Design optimisation—a step toward automated engineering

The first 50 years of scientific computing was mainly descriptive: simulation of a given scenario.

How does it behave? What happens if...?

Design optimisation is the next step and targets inverted questions like:

What should it look like in order to behave in a desired way? What is the best design that meets a set of design criteria?
Example applications

- Waveguides and antennas
- Structural optimisation
- Airfoil design
- Optimal control (eg trajectory planning)
- ...and many, many more!
A truly multi disciplinary application: 
*The logical clarinet*
Clarinet evolution

Existing instruments are result of an evolutionary process. Are there "better" instruments?

1680

1785

1820

1880

2000
Design goals

The geometry of an instrument must be such that the instrument
• Plays in tune
• Has a pleasant and equal timbre
• Neither feels unstable nor resistant to register change
• Can be manufactured

Are we ”trapped in a local minimum”?

Start from scratch: design the logical clarinet
The clarinet and its physics

Air flow is a function of pressure difference over reed and reed opening

\[ u = u_0 + ap + bp^2 + cp^3 \]

The reed works like a negative resistance

Under the right conditions, the system becomes unstable and starts to oscillate
A surprisingly complex system...

- Nonlinear system
- Wave propagation under viscous/thermal influence
- 3D effects
- Human hearing is very sensitive
Fortunately...

Different effects are localized to different parts:

- **Mouthpiece/reed** represented by a nonlinear equivalent circuit
- **Instrument** represented by linear 1D model
- **3D effects** mainly exterior

Nonlinear Viscous/thermal wave propagation, mainly 1D

Lossless, 3D
Circuit analogy model

- Impedance spectrum determines resonance frequencies
- A "peak" corresponds to a note
- Each fingering has its own unique impedance spectrum
An optimization problem

Find hole postions, diameters and lengths such that:

• The instrument plays in tune
• The register hole is effective
• The instrument has a balanced timbre throughout is playing compass

The last point is difficult to address in the objective function.

The hope is that design ”from scratch” will find a regular tonehole pattern.
Objective function

Peak frequencies are found from the impedance curve—one for each note (fingering)

Observed frequency \( f_1 \)  Desired frequency \( \tilde{f}_1 \)

\[
F = \frac{1}{2} r^T r, \quad r = \begin{bmatrix} f_1 - \tilde{f}_1 \\ f_2 - \tilde{f}_2 \\ \vdots \end{bmatrix}
\]

Deviations from desired resonance freqs. (+other terms such as peak heights etc.)

Solve the problem using a nonlinear LSQ solver or as a general nonlinear minimization problem (lsqnonlin or fmincon in Matlab)
Is this really a large problem?

- 60 parameters
- >60 residual terms
- Need to try many different choices of
  - Design bounds and constraints
  - Residual weighting
  - Initial solutions

Some constraints are too difficult to include in the objective function and have to be left for a posteriori evaluation.

The program must be reasonably interactive.

So, yes. It is in some sense large!
Optimisation strategy

- There are likely multiple solutions
  - Can get trapped in local minima
  - Some global optimisation strategy necessary
- The objective is a continuous function of the design variables
  - Makes a case for optimisation exploiting gradient information

A rapidly converging algorithm that can be started from many (random) initial solutions.
Results and conclusions

• Regular tonehole patterns are indeed found
• The algorithm runs fast enough for interactive use during the design process
• A workshop can use software to propose changes of existing instruments according to individual demands
• Prototype instrument shows promising properties
Pierre-André Taillard playing the logical clarinet