Examination of Organ Flue Pipe Resonator Eigenfrequencies by Means of the Boundary Element Method

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The aim of the investigations is the application of numerical methods for organ flue pipe research. The radiated sound of a flue pipe is very complex, affected by not only acoustical but also flow parameters. In order to reduce the problem complexity, a representative detail of the entire sound generating mechanism was selected, which can be numerically modelled. The eigenfrequency structure of a flue pipe resonator is a predominant component of the radiated sound spectrum and especially convenient for numerical simulations. The measurement procedure of the resonator frequency response (external acoustic excitation) was modelled by means of the Boundary Element Method and the obtained eigenfrequencies were verified by real measurement data. The effects of different tuning devices were examined by means of the mentioned method.

1 Introduction

Classical pipe organs have been playing an important role in European music life since time immemorial and their popularity seems to be unchanged. In the technical aspect, the pipe organ is one of the most complex musical instruments, thus several details can be chosen to do research on. It is essentially important to possess the correct rules of design and to comprehend the physical background of the traditional procedures applied by experienced organ builders. As a matter of fact, quite a lot of the steps are based on tradition not real physical consideration. This paper concerns the pipe research and the effect of tuning devices of flue pipes.

There are three ways of modern pipe research. The first one is the *analytical way*, which is efficient only in simple cases but able to reveal the principles of the sound generating process.

The *experimental way*, i.e. measurement, is the second chance of research. Special measurable pipes can be constructed for examining properties of the processes taking place in a pipe and the results can even verify the first analytical approach.

The third way is the *numerical modelling*. A proper numerical model gives the possibility to adjust the parameters of the pipe and examine the effects, without making real pipes. This paper is a summary of the authors' attempts to apply numerical methods for organ flue pipes.

2 Selection of the modelled detail and the proper numerical method

The properties of the radiated sound of a flue pipe are very complex, affected not only by acoustical but also flow parameters and they are even time-variant during the onset [1]. First of all, it is important to choose a detail of the entire sound generating process, which is suitable for acoustic numerical simulations.

According to the specific functions, a flue pipe consists of the following three basic parts (see Fig. 1):

- the *pipe foot*, which regulates and transmits the entering wind,
- the *mouth* (with the flue and the lips), which is the lower opening on the frontage of the pipe body and where an oscillating jet (the acoustic excitation of the resonator) is formed,
- the *resonator*, which propagates and transmits the waves of the jet oscillations; it has an open or stopped end often equipped with one of the conventional tuning devices.

In the acoustic aspect, the resonator is the most convenient for the numerical simulations as it has a characteristic eigenfrequency structure. The lowest eigenfrequency of the resonator determines the fundamental of the radiated sound. The resonator's length-to-diameter ratio, the area of openings and the applied tuning device have significant effects on the radiated higher frequency components [1, 2]. Finally, simulation results can be verified easily with real measurement data.

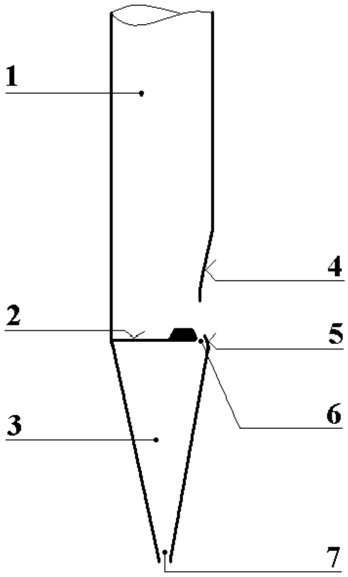

Figure 1: Cross section of a metal flue pipe
1. resonator 2. languid 3. pipe foot 4. upper lip
5. lower lip 6. flue 7. foot hole

2.1 First steps: applying the acoustic Finite Element Method

The geometry of the resonator (the simulation mesh of a real pipe) was constructed by means of the MSC.visualNastran for Windows 2002 software and the computations were completed by means of Sysnoise Rev 5.6 Acoustic and Vibro-acoustic modeller.

As a first approach, acoustic Finite Element Method was applied. The resonator was regarded as a cavity with boundary conditions representing the openings, and the acoustic modes of the system were determined. The boundary conditions were frequency-dependent admittance constraints derived from preceding measurements. Unfortunately, there are notable differences between the resulted eigenfrequencies of the modelled resonator and the measured ones. However, the provided colour maps of the eigenmodes are qualitatively correct: e.g. the asymmetrical location of the standing wave belonging to the fundamental eigenmode can be clearly seen in Figure 2 [1]. The maximum is slightly shifted towards the mouth having higher radiation impedance than the open end.

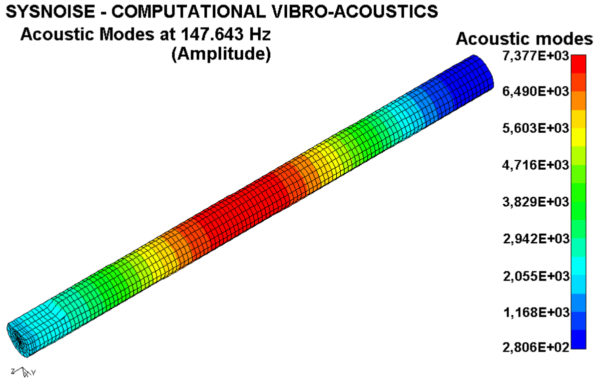

Figure 2: 147,643 Hz fundamental eigenmode of an open flue pipe resonator model (Pipe No.1.) computed by means of the FEM

2.2 Applying the acoustic Boundary Element Method

The same simulation mesh with minor transformation was used in indirect variational Boundary Element Method calculations. This approach modelled the *external excitation measurement*, the easiest way of measuring the eigenfrequencies of a pipe resonator [1]. In the course of the real measurement the pipe is placed in an anechoic room. A loudspeaker supplied by a white noise generator is used to produce an appropriate sound field, which excites the resonator in broad frequency band. The transfer function of the resonator will be determined with two microphones, one located in the pipe body (measuring the sound field in the pipe) and the second one located outside the pipe (measuring the direct sound of the loudspeaker). This curve has high peaks as the resonator amplifies the frequencies, which correspond to a certain eigenmode [1]. Thus, the eigenfrequencies of the pipe can be determined.

This measurement procedure can be imitated numerically, using the skinned mesh of the resonator and defining a distant spherical source for the excitation. Applying the Boundary Element Method for computations, the properties of the sound field (pressure, particle velocity, intensity, etc.) can be determined at any involved points ('field points') of the three dimensional space, in- or outside the resonator mesh. Examining sound pressure inside the pipe (on a long narrow stripe-shaped field point mesh), the resonance phenomena in the resonator can be demonstrated, and thus the eigenfrequencies of the surrounding pipe body can be determined. The spherical source of the model 'radiates' only at discrete frequencies, so that the whole acoustical problem had to be solved several times for different excitation frequencies to obtain an approximate frequency response of an inner field point. These simulations achieved much higher accuracy: the eigenfrequencies are more exact and the provided colour maps, similarly to the previous ones, show the eigenmodes correctly.

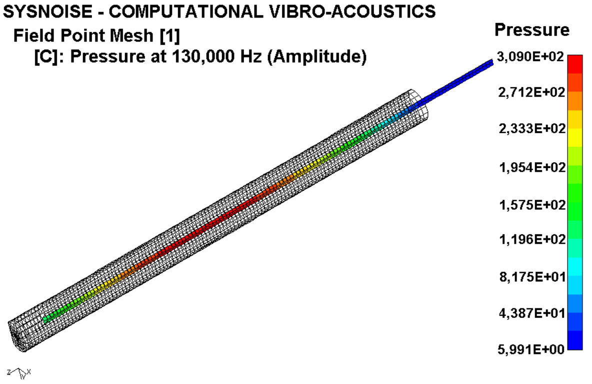

Figure 3: 130 Hz fundamental eigenmode of an open flue pipe resonator model (Pipe No.1.) computed by means of the BEM

The acoustic impedance at the openings is a function of the area and the frequency as well. Consequently, the frequencies related to the formed eigenmodes are not harmonic, but slightly stretched in the frequency domain [1]. The *stretching factor* represents this phenomenon numerically. (The stretching factor of an eigenfrequency is its ratio to the fundamental frequency.) Computed and measured eigenfrequencies together with the related stretching factors are shown in Table 1.

Table 1: First five eigenfrequencies of the measured and the BEM-simulated resonator (Pipe No.1.); stretching factors and frequency differences

	Measured		Simulated		
No.	Stretch.	f_{peak} [Hz]	f_{peak} [Hz]	Stretch.	Δf [Hz]
1	1	126,88	130	1	3,03 (2,3%)
2	2,029	257,44	262	2,015	5,44 (2,1%)
3	3,099	393,19	397	3,054	3,91 (1,0%)
4	4,15	526,56	533	4,1	6,50 (1,2%)
5	5,241	664,94	670	5,154	5,12 (1,0%)

Column 'Δf [Hz]' contains the absolute (and percentage) difference between simulated and measured frequency data. The error, in terms of percentage, is smaller than 3 % at each frequency, and the increasing tendency of the stretching at higher frequencies is also similar in both cases. Dimensions of the modelled pipe (Pipe No.1.) are indicated in the Appendix.

The effects of the conventional tuning devices were examined in the further simulations.

3 Examination of the effects of different tuning devices by means of the Boundary Element Method

3.1 Conventional tuning methods

3.1.1 'Cut-to-length' pipes

It is a general practice nowadays that organ builders make open metal pipes without any tuning device. The length of the resonator is cut precisely for the required pitch. These pipes are called ’cut-clear’- or ’cut to length’ pipes. If such a pipe goes out of tune, the organ builder will narrow or enlarge the open area with a special tuning cone. By adjusting the area of the opening, the acoustic impedance changes and causes the increase or decrease of the fundamental frequency.

3.1.2 Tuning roll

In order to modify the length of the resonator, organ builders cut a narrow stripe into the pipe body, starting at the open end and rolling it down to the required depth. This obviously changes the surface of the opening as well. The more the organ builder rolls down the stripe, the more he reduces the resonator length, thus increasing the fundamental. A pipe equipped with a tuning roll can be seen in Figure 3.

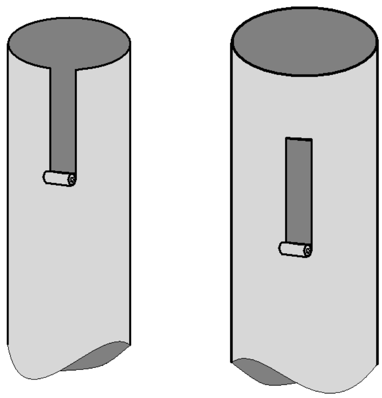

Figure 3: Tuning roll and tuning slot ("Expression")

3.1.3 Tuning slot ("Expression")

The tuning slot (called „Expression” in German) is similar to the simple tuning roll mentioned above. The main difference between the two devices, as it is seen in Figure 3, is that the stripe of the Expression does not start from the very end of the pipe, but a little lower. Thus it works as an open finger hole on a wind instrument. Acoustically, the openings can be regarded as parallel connected radiation impedances [2].

3.2 Effects of the dimensions of the tuning slot ("Expression")

The most challenging tuning device is the tuning slot (“Expression”), as pipes with this tuning device are said to be producing a particular sound. The results of preceding measurements show that this structure modifies the radiation impedance at the open end in such a way that the levels of the first 3-7 harmonics of the radiated sound increases compared to the sound of a cut-to-length pipe. Consequently, Expression significantly changes the perceived timbre [2]. It is also proven that a certain harmonic partial is amplified when it is close to a neighbouring eigenfrequency. Namely, the stretching of eigenfrequencies directly affects the envelope of the radiated spectrum and thus the 'colour' of the sound [1].

The question is, how the size and the position of the Expression opening influence the stretching factors.

Several numerical models were constructed to examine the effects of the Expression. Two different dimensions were adjusted: the pipe length above the opening and the width of the slot.

The dimensions of the modelled pipe (Pipe No.2.) are also indicated in the Appendix.

3.2.1 Adjusting the pipe length above the Expression opening

First, the pipe length above the opening was 0 cm (it is practically the case with the tuning slot) and it was increased gradually up to 160 mm. The more the pipe length was increased, the more the stretching factor decreased. The stretching factors divided by the number of the corresponding eigenfrequency (normalized stretching factor) is presented in Figure 4. Obviously, this newly defined factor is equal to unity when the appropriate eigenfrequency is neither stretched nor compressed, and in this case, the harmonic partial is effectively amplified. It is evident, that in case of the model (Pipe No.2.), the length of the pipe above the Expression opening is ideal around 50-70 mm, at 8-10 % of the whole resonator length. (The nominal length, 69,7 mm was determined correctly.) Far above this length, the eigenfrequencies become compressed and the amplification effect decreases again.

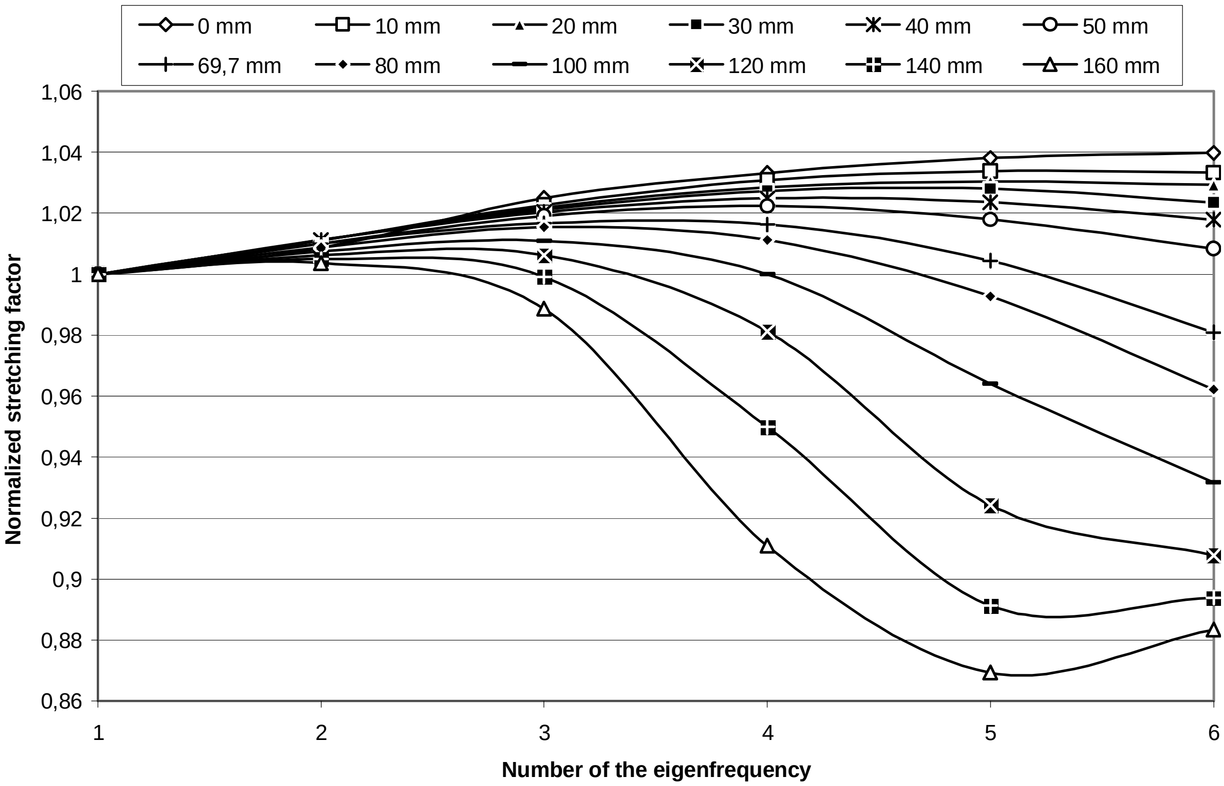

Figure 4: Change of the normalized stretching factor
in the function of the pipe length above the Expression opening

3.2.2 Adjusting the width of the Expression opening

In the second simulation, the pipe length above the Expression was set to the nominal value of 69,7 mm, and the width of the opening was gradually widened (the central angle corresponding to the opening was increased from 25,9° up to 225°). The previously defined normalized stretching factor is given in Figure 5. The first two models (25,9° and 45°) show the expected stretching factor function of the Expression, but as the opening gets wider, the influence of the added tube above the slot decreases. Basically, the structure approximates the cut-to-length pipe resonator, therefore, the stretching factor increases at higher eigenfrequencies.

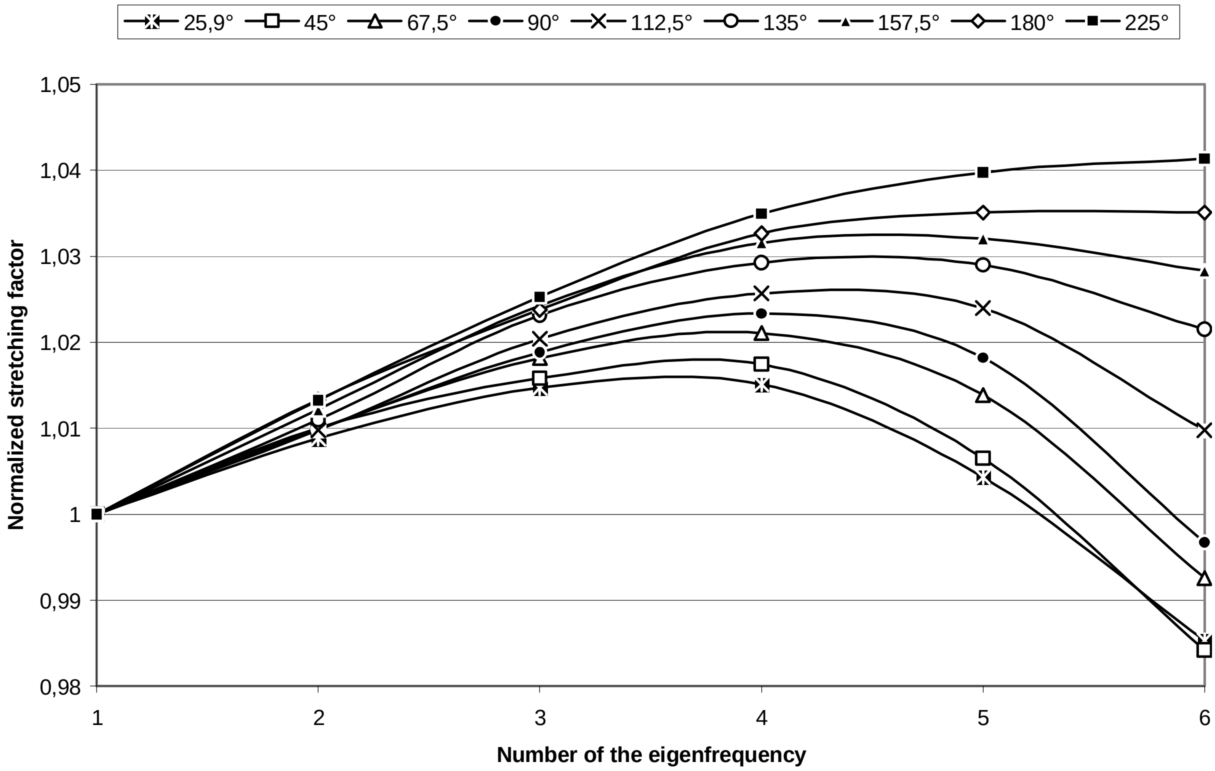

Figure 5: Change of the normalized stretching factor in the function of the width of the Expression opening

3.2.3 Tuning roll

The tuning roll can be regarded as a special tuning slot: the pipe length above the opening is 0 mm. The eigenfrequencies of such a resonator – as it is seen in Figure 4 in the case of 0 mm – are slightly stretched, similarly to that of cut-to-length pipes.

The previous slot-widening simulations were also completed for a resonator equipped with a tuning roll. The resulted stretching functions are given in Figure 6. These curves show very similar tendencies: in each case, independent of the width of the tuning roll, the stretching increases consistently with the frequency. In the aspect of the eigenfrequency stretching cut-to-length pipes and pipes with tuning roll are nearly identical.

4 Summary

Acoustical Finite Element Method and Boundary Element Method were applied to organ flue pipe simulations. The resonator frequency response measurement was modelled by means of the BEM, and the simulations provided reasonably accurate eigenfrequency data. Stretching factors of the eigenfrequencies were examined in the function of the applied tuning device. Cut-to-length resonators and resonators with tuning roll achieved almost the same result: the eigenfrequencies are slightly stretched, and the stretching increases with the frequency. This phenomenon decreases the amplification of the first 3-7 harmonic partials of the radiated sound. But a resonator, equipped with a well-designed Expression, shows a nearly harmonic series of eigenfrequencies, and, consequently amplifies the lower harmonic partials to a larger extent. This amplification is perceived as a 'rich' organ sound. The proper length of the pipe above the opening is around 8-10 % of the whole resonator length, while increasing the central angle, corresponding to the tuning slot width over 60°-70°, may degrade the positive effect.

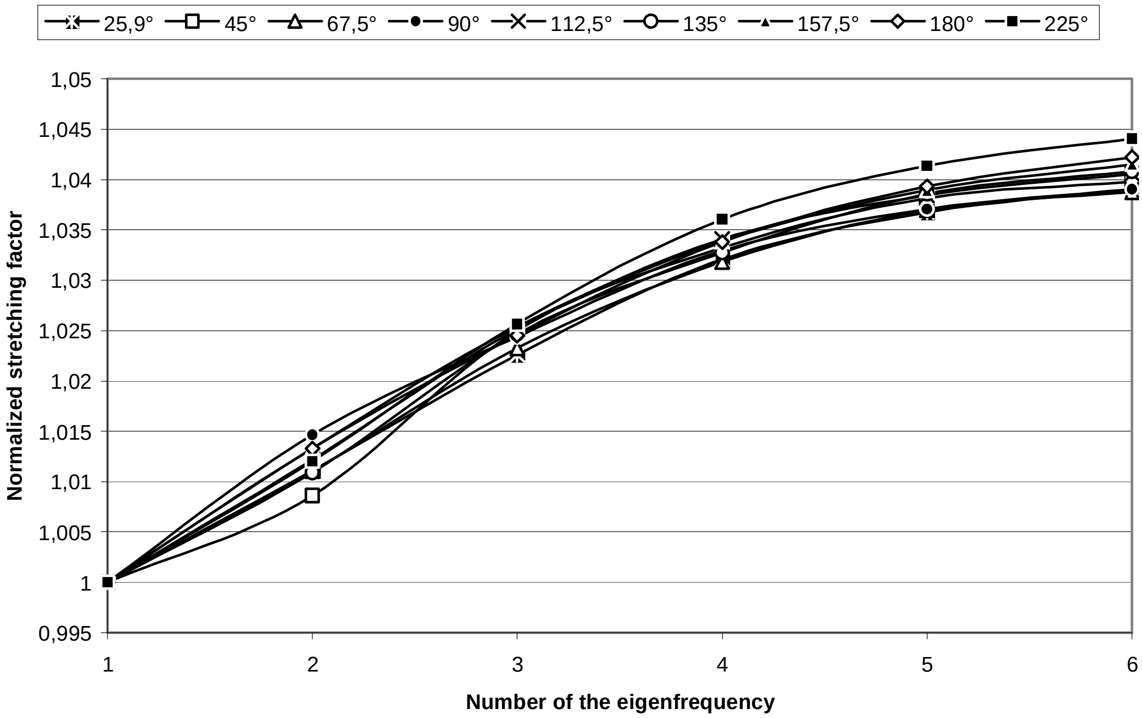

Figure 6: Change of the normalized stretching factor
in the function of the width of the tuning roll

Appendix

Dimensions of the simulated flue pipes:

- Pipe No.1. (without tuning slot)

  length of the pipe body: 1190 mm

  diameter of the pipe body: 82 mm

  cut-up height (distance between the lower and upper lip): 17 mm

  mouth width: 64 mm

- Pipe No.2. (with tuning slot)

  length of the pipe body: 834 mm

  diameter of the pipe body: 67 mm

  cut-up height: 13,5 mm

  mouth width: 53,5 mm

  distance between the languid and the lower line of the Expression: 72,05 cm

  nominal length of the pipe above the Expression opening: 67,9 mm

  nominal width of the Expression: 29,4 mm

  height of the Expression: 43 mm

References

[1] A. Miklós, J. Angster: *'Properties of the Sound of Flue Organ Pipes'*, Acta Acustica Vol. 86 (2000), pp. 611-622 (2000)

[2] A. Miklós, J. Angster: *'Sound radiation of open labial organ pipes; the effect of the size of the openings on the formant structure'*, Proc. Int. Symp. on Music. Acoust. (ISMA 98), Acoust. Soc. Amer. and Catgut Soc. Amer., Leavenworth, Washington, USA, pp. 267-272 (1998)