REAL-TIME PHYSICAL MODEL FOR SYNTHESIS OF SWORD SWING SOUNDS

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ABSTRACT

Sword sounds are synthesised by physical models in real-time. A number of compact sound sources are used along the length of the sword which replicate the swoosh sound when swung through the air. Listening tests are carried out which reveal a model with reduced physics is perceived as more authentic. The model is further developed to be controlled by a Wii Controller and successfully extended to include sounds of a baseball bat and golf club.

1. INTRODUCTION AND RELATED WORK

A number of models have been created to synthesise the sound of a sword sweeping through the air. Commonly these are based on one of two methods - signal based and physical models [1].

The advantage of a signal based model is that it is computationally inexpensive to replicate the spectrum of a sound using established techniques such as additive synthesis or noise shaping. A drawback of this approach could be relating changes in signal properties to the physical processes creating the sound. For example, an increase in speed of a sword not only changes the fundamental tone frequency but also the gain. Therefore changing one signal based property could lose realism in another.

Physical models aim to replicate the physics behind the sound generation process. Sounds generated by these models have the advantage of having greater accuracy in relation to the parameter settings but a drawback can be that the computational cost required to produce sounds is often high. Also, it is often the case that the sound effects cannot be adapted quickly to parameter adjustments and therefore not able to operate in real-time.

In the middle of these traditional techniques lie physically inspired models. This hybrid approach replicates the signal a sound produces but adds, to a greater or lesser extent, characteristics of the physics that are behind the sound creation. For a simple sword model this might be noise shaping with a bandpass filter with centre frequency proportional to the speed of the swing. A variety of examples

Figure 1. Computer generated character with a sword. Motion and dimension parameters can be determined by the game engine. (https://www.youtube.com/watch?v=zVvNthqKQIk)

of physically inspired models were given in [2]; the model for whistling wires being exactly the bandpass filter mentioned.

Four different sword models were evaluated in [3]. Here the application was for interactive gaming and the evaluation was focused on perception and preference rather than accuracy of sound. The user was able to interact with the sound effect through the use of a Wii Controller. One model was a band filtered noise signal with the centre frequency proportional to the acceleration of the controller. A physically inspired model replicated the dominant frequency modes extracted from a recording of a bamboo stick swung through the air. The amplitude of the model was mapped to the real-time acceleration data.

The other synthesis methods both mapped acceleration data from the Wii Controller to different parameters; one using the data to threshold between two audio samples, the other a granular synthesis method mapping acceleration to the playback speed of grains. Tests revealed the granular synthesis was the preferred method for expression and perception. One possible reason that the physical model was less popular could be the lack of correlation between speed and frequency pitch, which the band filtered noise had. This may also be present in the granular model.

A signal based approach to a variety of environmental

sound effects, including sword whoosh, waves and wind sounds was undertaken in [1]. Analysis and synthesis occur in the frequency domain using a sub-band method to produce coloured noise. In [4] a rapier sword sound was replicated but this focused on the impact rather than the swoosh when swung through the air.

A physical model of swords sounds was explored in [5]. Here offline sound textures are generated based on the physical dimensions of the sword. The sound textures are then played back with speed proportional to the movement. The sound textures are generated using computational fluid dynamics software, (CFD), solving the Navier Stokes equations and using Lighthill's acoustic analogy [6] extended by Curle's Method [7]. In this model, [5], the sword is split into a number of *compact sources*, (discussed in section 2), spaced along the length of the sword. As a sword was swept thought the air each source will move at a different speed and the sound texture for that source adjusted accordingly. The sound from each source was summed and output to the listener.

A Japanese Katana sword was analysed in [8] from wind tunnel experiments. A number of harmonics from vortex shedding were observed along with additional harmonics from a cavity tone due to the *shinogi* or blood grooves in the profile of the sword.

This paper presents the design, implementation and analysis of a real-time physical model that can be used to produce sounds similar to those of a sword swooshing through the air. It builds on previous work by the authors to create a real-time physical model of an Aeolian tone [9].

Our model offers the user control over parameters such as the arc length of the swing, sweep angles, top speed of the swing, dimensions of the blade as well as calculating what a listener will hear from a given observation point. The parameters available give the user the ability to model a wide variety of sword profiles, as well as other objects that produce similar sounds.

In addition a version of the model has been implemented with control mapped to the movement of a Wii controller. It is envisaged that many of the parameters available to the user could be set by a game engine and therefore the sounds generated directly. This would allow a correlation of the sound generated to the movement and weapon being used by a character, (Fig. 1).

2. THEORY

The fundamental aeroacoustic sound created when a cylinder is swung through the air is the Aeolian tone. This sound is generated when fluid passes around the cylinder and vortices are shed from opposite sides. This causes oscillating lift and drag forces which in turn produce tones of different strength and propagation directions.

A brief overview of the Aeolian tone will be given here, including some fundamental equations. For greater depth the reader is directed to [9].

Harmonic	Frequency	Gain
Drag dipole fundamental (f_d)	$2f_l(t)$	$0.1\overline{I_l}(t)$
Lift dipole 1st harmonic	$3f_l(t)$	$0.6\overline{I_l}(t)$
Drag dipole 1st harmonic	$4f_l(t)$	$0.0125\overline{I_l}(t)$
Lift dipole 2nd harmonic	$5f_l(t)$	$0.1\overline{I_l}(t)$

Table 1. Additional frequencies and gains as a function of the lift dipole fundamental frequency $f_l(t)$.

2.1 Tone Frequency

Strouhal (1878) defined a useful relationship between the tone frequency f_l air speed u and cylinder diameter d (Eqn. (1)). The variable S_t is known as the Strouhal number.

$$S_t(t) = \frac{f_l(t)\,u(t)}{d} \tag{1}$$

As air flows around cylinder, vortices are shed causing a fluctuating lift force normal to the flow dominated by the fundamental frequency, f_l. Simultaneously a fluctuating drag force is present with frequency, f_d, twice that of the lift frequency. The drag acts in line with the the air flow and it was noted in [10] that, "*The amplitude of the fluctuating lift is approximately ten times greater than that of the fluctuating drag.*"

It was shown in [7] and confirmed in [11] that aeroacoustic sounds, in low flow speed situations, could be modelled by the summation of *compact sources*, namely monopoles, dipoles and quadrupoles. Aeolian tones can be represented by dipole sources, one for the lift frequency and one for the drag; each source includes a number of harmonics.

The turbulence around the cylinder affects the frequency of the tones produced. A measure of this turbulence is given by a dimensionless variable, the *Reynolds number*, R_e, given by the relationship in Eqn. (2).

$$R_e(t) = \frac{\rho_{air}\,d\,.u(t)}{\mu_{air}} \tag{2}$$

where ρ_{air} and μ_{air} are the density and viscosity of air respectively. The value of the Strouhal number has been found to be related to the Reynolds number. An experimental study of this relationship was performed in [12], giving the following equation:

$$S_t(t) = \lambda + \frac{\tau}{\sqrt{R_e(t)}} \tag{3}$$

where λ and τ are constants and given in Table 1 of [12], (additional values are calculated in [9]). The different values represent the turbulence regions of the flow, starting at laminar up to sub-critical.

With the Strouhal number obtained, diameter and air speed known, we can apply them to Eqn. (1) and obtain the fundamental frequency, $f_l(t)$, of the aeolian tone, generated by the lift force. Once $f_l(t)$ has been calculated, we can calculate the drag dipole frequency and harmonics as shown in Table 1.

Each frequency peak has a bandwidth which is proportional to the Reynolds number. Equations to calculate the bandwidth are given in [9], derived from data published in [13].

2.2 Source Gain

Once the fundamental frequency has been calculated the source intensity and propagation pattern can be calculated. The time-averaged Acoustic Intensity $\overline{I_l(t)}$ (W/m^2), of an Aeolian tone lift dipole source and the time-averaging period are given in [14]. The time-averaged Acoustic Intensity is given as:

$$\overline{I_l(t)} \approx \frac{\sqrt{2\pi}\kappa^2 S_t(t)^2 l \, b \, \rho \, u(t)^6 \sin^2\theta \cos^2\varphi}{32c^3 r^2(1 - M(t)\cos\theta)^4} \quad (4)$$

where $M(t)$ is the Mach number; $u(t)/c$, where c is the speed of sound. The elevation angle, azimuth angle and distance between listener and source are given by θ, φ, and r respectively. The constant κ is set to 1. The correlation length, l, given as a multiple of diameters, indicates the span-wise length that the vortex shedding is in phase; after this the vortices become decorrelated. $\overline{I_l(t)}$ is applied to the fundamental frequency and scaled for the harmonics as shown in Table 1. The gain for the drag dipole is obtained from [10] and the lift dipole harmonics values from [15]. The drag dipole 1st harmonic was witnessed in computational simulations and added at the appropriate value.

2.3 Wake Noise

As the Reynolds number increases, the vortices diffuse rapidly and merge into a turbulent wake. The wake produces wide band noise modelled by lateral quadrupole sources whose intensities vary with $u(t)^8$ [16].

It is noted in [16] that there is very little noise content below the lift dipole fundamental frequency. Further, it has been shown in [17] that the roll off of the amplitude of the turbulent noise, above the fundamental frequency is $f_l(t)^{-2}$. An equation for calculating the wake noise is given in [9].

3. IMPLEMENTATION

Implementation of each individual compact source is given in [9]. The basic concept of the sword model is to line up a number of the compact sources to recreate the sound created as a blade swings through the air.

Like the original compact source model presented in [9], this model was developed using the Pure Data programming platform. The intensity given in Eqn. (4) is time averaged which caused an issue for this model due to the swing time being shorter than the averaging process. In the case of this model the intensity was implemented as an instantaneous value.

Our model has been given a simple interface to allow the user to manipulate physical properties such as sword thickness, length, top speed at the tip and sweep angles. Some or all of these parameters can be directly mapped to graphics and animation within a game environment.
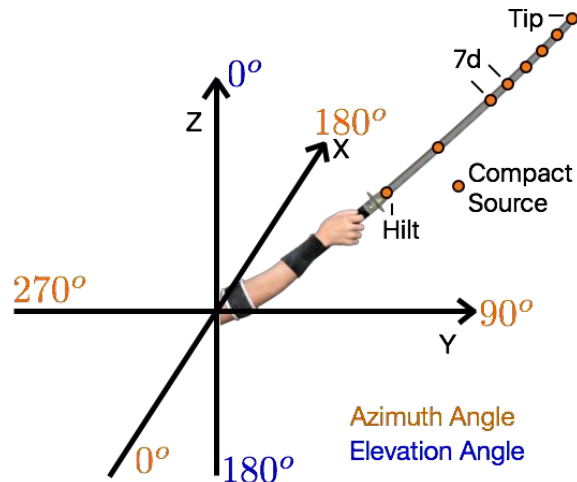

Figure 2. Position of 8 compact sources and coordinates used in sword model.

For ease of design the thickness down the blade of the sword was taken as a linear interpolation between the thickness set at the hilt and that set at the tip. The diameter of an individual source is then set as the thickness corresponding to its position on the blade. Equation 4 shows that the gain is proportional to $u(t)^6$. As a sword arcs, the blade moves faster through the air at the tip than at the hilt. Hence the sources nearer the tip will have a greater influence over the sound generated than those nearer the hilt.

Eight compact sources were used to model the sword in our model. Two of the sources were fixed at the tip and the hilt. Five sources were then positioned back from the tip at a spacing of 7 times the diameter, d. The final source was placed equidistant between the last one from the group at the tip and the hilt. This is illustrated in Fig. 2.

This positioning of the six sources at the tip was equivalent to each source having a set correlation length of $7d$, (see Section 2.2). A range of correlation values from $17d$ to $3d$ are given in [18] depending on Reynolds number. A plot showing similar values is shown in [19]. [1]

In this model, the position of the sources has to be chosen a priori to the calculation of the Reynolds number; the value $7d$ was chosen as a compromise, covering a reasonable length of the sword for a wide range of speeds (hence Reynolds numbers). For illustration, examining a sword of length 1.117 metres long and diameter ranging from 0.013 metres at the hilt to 0.008 metres at the tip. The 8 sources positioned as described equates to a coverage of 43% of the blade length being represented by the sources. As shown in Fig. 2 the positioning of sources capture the area which contributes most to the sound.

The coordinate system used for the model is shown in Fig. 2. The centre of the sword arc is at the origin and each sweep is set as circular. The distance travelled by each source during an arc is a great circle on a sphere with a radius equal to that of the source.

The user specifies the sweep of the sword by setting a start and finish for azimuth and elevation angles as well as

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[1] In [5] the correlation length of $3d$ was used; the number of sources set to match the length of the sword.
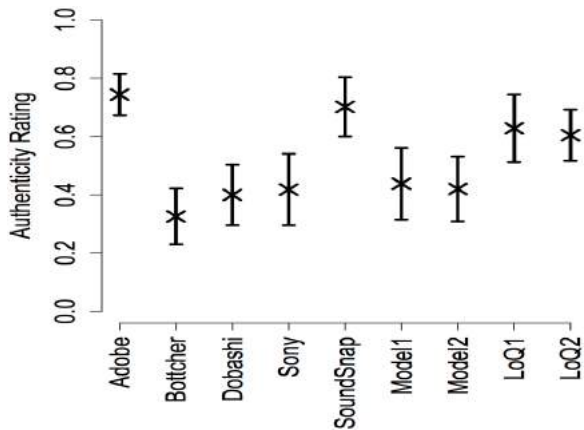
Figure 3. Sword sounds clips rated by authenticity. (Mean and 95% confidence shown.)

Source	Classification	Duration (ms)
Adobe	Sample	481.7
Bottcher	Granular / Additive mix	218.6
Dobashi	CFD	496.7
Sony	Sample	1138.4
SoundSnap	Sample	161.0
Model 1	Physical Model	917.1
Model 2	Physical Model	928.8
LoQ 1	Physical Model	731.1
LoQ 2	Physical Model	1079.7

Table 2. Clips used for listening test.

the top speed of the tip. It is presumed the sword starts and finishes at rest and also uniform acceleration and deceleration; the average speed is $top\ speed/2$. The blade reaches top speed when it crosses the xy plane, an azimuth angle of $180°$. Any graphical character swinging the sword can be oriented in any direction and the elevation and azimuth adjusted accordingly. Knowledge of the distance travelled and average speed enables us to calculate the ramp time up to top speed as well as back to rest for each source.

We know that the sword sweep is a 2 dimensional plane in a 3 dimensional environment. The observer is taken to be a point in that environment. To calculate the elevation and azimuth of each source to observer a projection matrix is created to find the position in the plane of the sword perpendicular to the observer. The angles can be calculated using trigonometry identities as can the overall distance between the observer and individual sources.

Panning is included as the sound moves across the xy plane as well as the Doppler Effect. It was shown in [20] that the addition of the Doppler Effect increases the natural perception. This effect is taken into account when the sword is moving towards or away from the observer and frequencies adjusted accordingly.

4. RESULTS AND ANALYSIS

4.1 Listening Test

A listening test was carried out using [21], asking participants to rate a number of sounds for authenticity. Table 2 classifies the sounds used for the test; all sounds were wav files. The sample duration was calculated as the total length of the sample, where the loudness was greater than -90 dBFS. A total of 25 participants took part, aged from 16 to 77 years old, with a mean age of 39.1 years and standard deviation of 16.8, (one participant declined to state their age). The sounds chosen included 3 samples from effects libraries, a recording of the synthesis model by [3], as well as one from [5]. Users were provided with an interface that allowed them to play back each sound sample and rate the sounds on a scale. Participants auditioned the sounds through a pair of AKG K550 Headphones - this was done

to remove any natural acoustic impact of the sounds being played in any environment. The users were asked to rate the sounds in terms of "authenticity". Sample order was randomised and all samples were loudness normalised [2]. Participants were allowed to audition any sample as many times as they wanted, and on average, participants played each sound 8 times.

Two different sword sounds from our model were used, one thin and long and one thicker and slightly shorter (Model 1 and Model 2). Lower quality versions of the two swords sounds were also generated, keeping all the dimensions identical, (LoQ1 and LoQ2). The lower quality versions use a model with reduced knowledge of the physics with a fixed the Strouhal number St at 0.2, removed the wake noise source and fixed the bandwidth of the fundamental and harmonics, all filters Q value set to 10.

The mean authenticity rating plus 95% confidence intervals (approximately two standard deviations) is shown in Fig 3. The sampled sounds taken from the Adobe and Soundsnap libraries are clearly rated the highest. This is not surprising as it is possible every effort has been spent mastering the sounds to achieve the best effects. The sound rated the worst was the one taken from [3]. It is know that this sound was not generated for authenticity, rather perception and preference.

For a deeper analysis we performed a one-way ANOVA to determine the impact of synthesis method on the user authenticity ratings, and a significant effect is identified $(F(8,216) = 0.62, p<0.00001)$. A Tukey post-hoc test was performed to determine the comparison between each individual synthesis method, and the results are presented in Table 3.

It can be seen from Table 3, that all synthesis methods apart from the two low quality methods are significantly different from the recorded samples. The low quality synthesis methods are both considered as indistinguishable from the recorded sound samples. It should also be noted that the low quality synthesis is not significantly different from any many synthesis methods. As such, these synthesis methods did not significantly out performed any other method, other than Bottcher.

Analysis shows that the sounds generated by our sword model has a perceptual rating on par with the Sony recorded sample as well as a granular / additive synthesis

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[2] in compliance with ITU-R BS.1534-1

	Adobe	Bottcher	Dobashi	Sony	SoundSnap	Model 1	Model 2	LoQ 1	LoQ 2
Adobe	.	****	***	***	-	***	***	-	-
Bottcher	****	.	-	-	****	-	-	**	*
Dobashi	***	-	.	-	***	-	-	-	-
Sony	***	-	-	.	**	-	-	-	-
SoundSnap	-	****	***	**	.	**	***	-	-
Model 1	***	-	-	-	**	.	-	-	-
Model 2	***	-	-	-	***	-	.	-	-
LoQ 1	-	**	-	-	-	-	-	.	-
LoQ 2	-	*	-	-	-	-	-	-	.

Table 3. Results of a Tukey post hoc test. **** = $p<0.0001$, *** = $p<0.001$, ** = $p<0.01$, * = $p<0.05$, - = $p> 0.05$

technique [3] and an offline CFD technique [5]. The advantage of our model being the ability to relate the output sound to parameters of a physical sword swinging through the air and its real-time operation.

The surprise in the listening test is the results for the low quality model. Although they did not significantly out perform any other method they were also considered perceptually indistinguishable from the top performing recorded samples. One reason could be due to the fixed bandwidth which give the impression of more turbulence as the sword sweeps; the full models sound thinner in comparison. It should also be recognised that the full model is intended to replicate the physics as accurately as possible, as would be produced in an anechoic chamber.

Although there is no conclusive evidence, it is felt that fixing the Strouhal number at 0.2 and removal of the wake sound within each source will have a lower perceptual effect than fixing the bandwidth. Computationally this saves a number of calculations which was one of our goals when developing the model. It is possible that removing one of the lift harmonics and the drag harmonic will also have little effect on the perception of authenticity for this model but again save on computations.

It is reasonable to presume that participants could be more familiar with sword sound effects than the actual sounds generated when physically using a sword. Participants were offered the chance to comment on any sound file they wished. A comment on Model 1 was *"seems to be a very small object, (almost 'too small')"* and on the low quality version of the same sword, LoQ1, is *"a very plausible light weight sword"*. Similarly for Model 2 a comment was *"the frequencies constituting the sound seem awkward / implausible"* and for equivalent the low quality model, LoQ2, *"good sound"*, *"arteficial"* and '*"sounds model like scrapping fabric"*.

4.2 Interactive Test

To allow participants to interact with the model a Wii Controller was linked to a MacBook via bluetooth and a free trial version of the commercial software, OSCulator [3] . The angular velocity values from the gyroscope in the Wii controller are mapped to the speed of the source at the hilt and scaled depending on radius of the remaining sources.

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[3] https://osculator.net

Figure 4. Test participant swinging the Wii Controller synthesising a golf swing sound.

It was decided to fix the listener position in this model since the elevation and the azimuth values obtained when moving the Wii Controller drifted, which would created confusing pan values when swinging.

The start model given to users was equivalent to a broom handle of 1.5 metres long and 0.024 metres thick. This allowed the participant to get used to the model, including how fast they had to swing to get the results required. The gain was always set low but increased if requested.

Once participants were familiar with the broom handle model, four other presets were demonstrated including the two swords that were within in the listening test. We extended the sound effects that may be generated by our model by adding in the dimensions of a baseball bat and that a golf club. Fig. 4 shows a participant interacting with the golf club synthesis model.

Once participants had interacted with the presets to their satisfaction they were invited to change the dimensions of the model to their desire. Blade thickness and length, as well as gain, could be varied by the participant by using the buttons on the Wii controller. More often than not, participants who wished to change the parameters were guided by the author. The usual request was to make a sword in the region of 3 metres long, more than likely too heavy and cumbersome in reality but fun to interact with. The sword demo GUI is shown in Fig. 5.

One participant asked the author to replicate the sound of a pickaxe and another a martial arts Bo staff. Both stated they were satisfied with the results. Once they had finished interacting with the models, participants were asked to fill
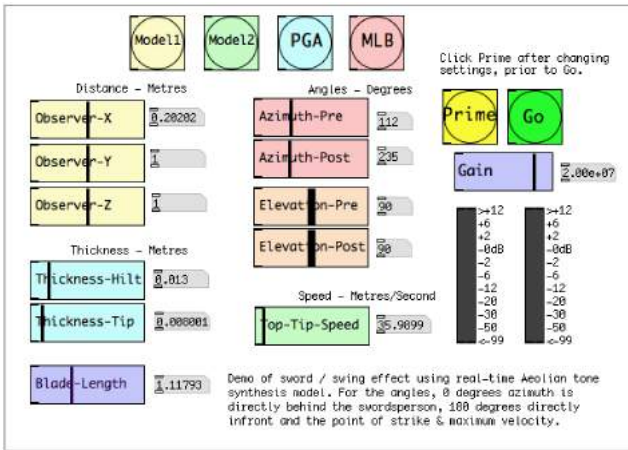
Figure 5. Pure Data GUI for the sword, golf club and baseball bat sounds.

	Mean Rating (Standard Deviation)
The experience was enjoyable.	4.46 (0.65)
I could achieve the sounds I wanted.	4.08 (0.63)
The sounds correlated with my movements.	4.38 (0.75)
I found the effect and interface easy to use.	4.08 (0.98)
I would use these sounds in a game.	3.92 (1.16)
Please rate the quality of the sounds.	4.19 (0.75)

Table 4. Ratings for Wii Controller interaction. (Ratings from *strongly disagree = 1* to *strongly agree = 5*, except the last question, *very poor = 1* to *excellent = 5*.)

in a short questionnaire, stating how much they agreed with set statements, shown in Table 4.

Results show that participants overwhelmingly enjoyed interacting with the models. There is also a very high result for the correlation between participants' movements and the sounds generated, a fundamental goal of the physical model. A number of comments were recorded after the interactive tests which included *"Fun experiment, the sounds drove me on and created a sense of excitement"*, *"..it's the lack of weight on the tip.."* and *"The parametrisation of the sound model made a lot of sense"*. [4]

5. CONCLUSION

The swoosh sound generated from a sword as it is swung through the air is successfully replicated by an implementation of a number of compact source models given in [9]. Vortex shedding frequencies are generated in real-time while calculating intensity, bandwidths and harmonics.

Listening tests show model with reduced physics is perceived as more authentic than the model with higher phys-

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[4] A copy of all the sound files used in the perceptual evaluation test as well as a copy of the PureData sword demo model can be obtained from https://code.soundsoftware.ac.uk/projects/physical-model-of-a-sword-sound.

ical knowledge. The sounds of Model 1 and Model 2 perceived as just as authentic as other synthesis models; sample sounds were rated highest for authenticity out of all the sounds.

The model was successfully adapted to allow interaction with a Wii Controller and extended to include sounds of a baseball bat and golf club, as well as various gigantic swords and a pickaxe. Participants found this experience fun and engaging but also highlights the versatility of the model to synthesise bats and clubs. The range of sound effects this model is able to synthesise is an area for future research.

The linking of the sword model to a game engine or virtual reality environment would be of great value. This would give users the ability to visualise actions increasing the correlation between sound and movement.

It will be of value to investigate the balance between more compact sources and reducing the physics included in the compact source model. In contrast, adding the natural vibration frequency of the sword may have an effect, especially if the shedding frequency and the natural frequency match. Including cavity tones as witnessed by the wind tunnel experiments in [8], will increase the variety of profiles that can be modelled.

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