THE VOICE OF THE MECHANICAL DRAGON

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ABSTRACT

The sound radiation of a swinging corrugated tube (Hummer) has been measured under anechoic and semi-anechoic conditions. The whistling is induced by synchronized vortex shedding at each corrugation coupled to an acoustic standing longitudinal wave. In an earlier paper the Hummer was hand-driven. In order to eliminate this human factor, the instrument is driven mechanically. This considerably enhances the agreement between measured sound radiation and prediction by a model assuming at the open ends acoustic velocity fluctuations of 5% of the main flow velocity through the tube. These pipe terminations act as monopole sound sources. Significant deviations from theory still remain. In particular the amplitude modulation of the sound, due to interference between the two sources, is deeper than predicted. Experiments also show the possible coexistence of two acoustic modes, which is not considered in the theory. The possible elongation of the tube by centrifugal force and flutter due to vortex shedding appears to be negligible.

1. INTRODUCTION

In an earlier paper [1] we considered the sound production and radiation of a swinging corrugated tube. This musical toy is called a Hummer [2]. In musical applications it is called the Voice of the Dragon [3], [4]. The Hummer considered here has a length $L = 0.750$m and an inner diameter $D = 25$ mm. The corrugation pitch length is $W_p = 7.0$ mm. The pipe inlet has a horn shape ($L_{con} = 20$ mm) followed by a smooth pipe segment ($L_{smith} = 30$ mm), forming a handle (Fig. 1).

When the pipe is hold at one end and swung, it acts as a centrifugal pump. This induces a flow through the pipe with a velocity U [1]. Vortex shedding, at each cavity formed by the corrugations, couples with longitudinal acoustic standing waves: modes of the open-open tube with resonant frequency $f_n \simeq nc_{eff}/(2L)$ ($n = 1, 2...$), where c_{eff} is the effective speed of sound in the tube [1]. This synchronizes the vortex shedding along the pipe for critical ranges of the Strouhal number $f_n W_p/U$. The resulting

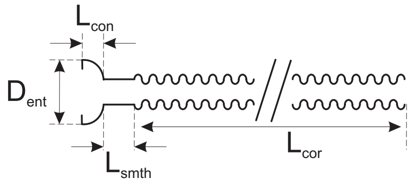

Figure 1. Geometry of the Hummer: $L = L_{for} + L_{smith} + L_{con} = 75$ cm , $D = 25$ and $D_{ent} = 40$ mm.

loud whistling saturates as a result of non-linearity. The acoustic velocity fluctuations ,u' , have then typically a dimensionless amplitude, u'/U, of the order of 5%, where u' is the amplitude of the velocity oscillation at the open pipe terminations. One expects that the non-linear saturation mechanism, which stabilizes the limit cycle, prevents the coexistence of two acoustic modes [5], [6], [7]. Therefore the internal acoustic field should be a line spectrum dominated by multiples of the fundamental $f = mf_n$ ($m = 1, 2...$).

The open terminations radiate as coherent monopoles. The radiation is isotropic because $2\pi f_n D/c_0 \leq 0.5$, where c_0 is the speed of sound in free space [8]. The interference pattern induced by these two sources rotates with the pipe. In addition to that the rotation induces a Doppler effect. The perceived frequency of the rotating sound source varies up to a semi-tone. A theoretical model (section 2) taking these effects into account has been proposed in our earlier paper [1]. The radiated sound spectrum is accurately predicted, but the model was unable to explain the observed amplitude modulation. As the instrument was swung by hand, we expect that the rotation speed cannot be constant. Also the position of the microphone is difficult to determine accurately. Furthermore the pipe is bended and oscillates. We therefore expect a variation in the flow velocity, U, through the pipe. As observed by Kristiansen [9] such a slow modulation of the flow velocity U induces a complex acoustic response of the pipe. There is a considerable delay between variations in U and the modulation in the amplitude u' of the acoustic oscillation.

In order to eliminate such uncertainties, experiments have been carried out with a mechanically driven Hummer. The experiment is inspired by the pioneering work of Silverman and Cushman [3]. The Hummer is mounted on a bicycle wheel driven by an electrical motor (section 3). The effect of reflections on the floor of the semi-anechoic room was investigated by placing a sound absorbing mat on the floor between the Hummer and the microphone. The present paper describes primarily the results obtained (section 4).

We furthermore discuss some mechanical aspects of the problem (section 5). It has been suggested that the elongation of the Hummer under influence of the centrifugal acceleration results in a flattening of the pitch when increasingly high pipe modes are excited [10]. Another mechanical problem is that vortex shedding in the wake of the rotating tube can couple with mechanical oscillation modes of the tube, resulting into flutter and associated transversal motion of the tip of the tube.

2. THEORY

Based on the measurements presented by Nakiboglu at al. [1] we estimate the amplitude, u', of the velocity fluctuations at the open pipe termination from:

$$u'/U = 0.05. \tag{1}$$

The flow velocity U is calculated from the measured angular rotation velocity Ω:

$$U = \Omega\sqrt{\left(\frac{{R_2}^2 - {R_1}^2}{1 + 4c_f\frac{L}{D}}\right)} \tag{2}$$

where R_1 is the radius of rotation of the pipe inlet, R_2 is the radius of rotation of the pipe outlet, L is the pipe length, $c_f = 0.0178$ is the friction coefficient of the pipe messured by Nakiboglu et al. [1]. The amplitude Q of the oscillating monopole sources is:

$$Q = u'\frac{\pi D^2}{4} \tag{3}$$

The pressure oscillation $p'_i(\vec{x}, t)$ radiated by monopole Q_i ($i = 1, 2$ from position $\vec{x}_i$, reaching the observer at $\vec{x}$ at time t is given by [11]:

$$p'_i(\vec{x}, t) = (-1)^{i(n+1)}\frac{\partial}{\partial t}\left[\frac{Q\cos(\omega t_{e,i})}{4\pi|\vec{x} - \vec{x}_i(t_{e,i})||1 - M_i(t_{e,i})|}\right] \tag{4}$$

where the angular frequency is $\omega = 2\pi f_n$ and the emission time is found by solving the equation:

$$t_{e,i} = t - \frac{|\vec{x} - \vec{x}_i(t_{e,i})|}{c_0} \tag{5}$$

In principle the oscillation frequency is close to the pipe resonance frequency $f \simeq f_n$. In our model, we will however use the measured oscillation frequency f, corresponding to the peak in the spectrum of the radiated sound. The formula takes into account that the oscillating velocities for even modes $n = 2, 4, 6...$ have opposite phase at inlet and outlet of the pipe. The source position is given by:

$$\vec{x}_i(t_{e,i}) = (R_i\cos(\Omega t_{e,i}, R_i\sin(\Omega t_{e,i} + \phi_i), z_i) \tag{6}$$

In our experiments the Hummer is in the horizontal plane $z_i = h$. The relative Mach number is given by:

$$M_i = \frac{1}{c_0}\frac{\partial|\vec{x}_i(t_{e,i}) - \vec{x}|}{\partial t_{e,i}} \tag{7}$$

Figure 2. Fixation of the Hummer on the Wheel and detection of wheel rotation.

where c_0 is the speed of sound of ambient air. The acoustic field without reflections on the floor is simply the sum of the two contributions p'_i. When the floor is reflecting we have to add to this the contribution of the images with $z_i* = -h$ at $\vec{x}_i* = (R_i\cos(\Omega t_{e,i}*, R_i\sin(\Omega t_{e,i}*+\phi_i), z_i*)$. In order to calculate the various contributions at the same observers time, we can solve equation (5) for the emission times for each source. Alternatively we can calculate for given emission times the contributions as functions of the observer time t. The reception time t is calculated explicitly for each source from equation (5) for given $t_{e,i}$. The acoustic field at a given observer time is obtained from these data by interpolation.

3. EXPERIMENT

The Hummer was attached to the spikes of a 26" bicycle wheel. The inlet $i = 1$ was fixed by means of a plastic ring close to the axis of the wheel ($R_1 = 0.10$ m). Another plastic ring was fixing the tube at the end of a spike (Fig. 2). The outlet $i = 2$ is at a distance $R_2 = 0.71$ m from the wheel axis. At rest $\phi_2 = 0$ and $\phi_1 = -2\pi/3$. The positions of the monopole sources are corrected for an estimated end-corrections of the pipe , $\delta = 0.3D$ cm for each side. Therefore the distance $|\vec{x}_2 - \vec{x}_1|$ exceeds the pipe length by 15 mm.

The angular velocity Ω is positive in the (x, y, z) right-handed coordinate system with the vertical z-axis along the wheel axis. As shown in the photograph (Fig. 3) a second Hummer is placed on the wheel. This Hummer is plugged and does not whistle but provides mechanical balance to the wheel.

The wheel is mounted on a horizontal optical bench, a 1 m long aluminum tube/rod of "square" cross section (0.1 m x 0.1 m). This horizontal rod mounted to a 1.90 m tall vertical rod. The sides of these hollow rods are plugged by sound absorbing foam. The wheel axis is at 0.2 m from the front end of the horizontal rod. The vertical rod is at 0.6 m from this front end. The electrical motor is fixed to the horizontal rod near the back end. A bicycle chain is used to transmit the rotation to the wheel. The Hummer lays at the height $h = 2.23$ m above the floor. The axis of the wheel in a corner of the semi-anechoic room at about 1 m from both walls. The semi-anechoic room has a volume of 100 m^3

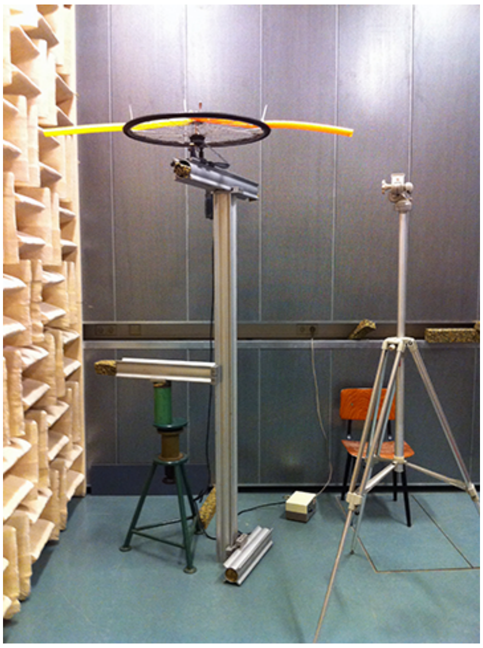

Figure 3. Overview of the set-up with reflecting floor.

and a cut-off frequency of 300Hz. A wind tunnel nozzle and a table, which could not be removed from the room, are placed at the opposite side of the room. They are covered by acoustic foam (10 cm thick mattresses). Unfortunately the table forms a resonating cavity with an height of 0.54 m which pollutes results with frequencies around 630 Hz. The frequency of this half wave length mode of the table almost coincides with the frequency $f_3 = 635$ Hz of the third acoustic mode of the Hummer.

A "distant" microphone (BK 1/2" type 4190) is placed at $\vec{x}_D = (1.58, 0, 1.68)$ m. An identical "close" microphone is placed at $\vec{x}_C = (0.42, 0.72, 2.03)$ m. The holder of the close microphone can be seen on the right of the set-up (Fig. 3). The microphone signals are preconditioned by an amplifier/batteries power supply (BK type 5935L). A four channel 16 bit ADC (National Instruments) is used for data acquisition. The signals were sampled at 10 kHz for 20 s. One channel is used to detect the electrical signal picked up by a coil upon passage of a small magnet fixed to one of the spikes. This signal is used to measure the period of rotation of the wheel $T = 2\pi/\Omega$.

Experiments were carried out with and without a sound absorbing mat placed halfway between the distant microphone and the vertical support rod. The mat of porous foam had a surface of 1 m^2 and was 8 cm thick.. It was laid 8 cm above the ground on a few 10 cm wide strips of the same foam material. On top of the mat three (30 cm high sound absorbing) wedges as the ones covering the wall are placed (Fig. 4). Once the rotation speed of the wheel was established a first measurement was carried out with this non-reflecting floor. The mat was then removed without stoping the wheel and the experiment was repeated with reflecting floor at the same rotation speed. The rotation speed was chosen to obtain a loud stable pure whistling tone.

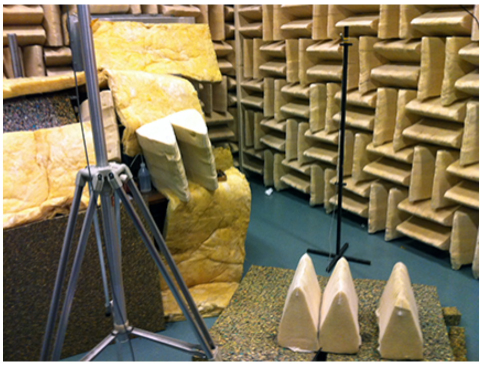

Figure 4. Sound absorbing mat on the floor between the wheel and the distant microphone.

Most experiments were carried out with the original Hummer with handle near the wheel axis. Some additional measurements were carried out with inverted Hummer and sound absorbing floor. A final series of measurements was carried out with a Hummer from which the horn had been removed (2 cm shorter pipe).

4. RESULTS

In Fig. 5 we compare the measured and predicted signals of the close microphone for $n = 2, 3, 4$ and 5, the four whistling modes, for the non-reflecting floor. In Fig. 6 we show the same results for the distant microphone.

Stable signals were obtained for the acoustic modes $n = 2, 3$ and 4. The first mode (n=1) did not whistle. In some experiments the fifth mode ($n = 5$) is "polluted" by a significant contribution of the fourth mode ($n = 4$). Both modes were stable and are clearly seen in the spectrum (Fig. 7). This contradicts the assumption that due to non-linear saturation effects, two modes cannot coexist. Increasing the rotation velocity one obtains a "pure" mode $n = 5$ oscillation.

Globally the theory does reasonably predict the Sound Pressure Level (within 2 dB). As explained above, the resonance of the air under the table did pollute the results around 630 Hz, which corresponds to f_3. The theory does qualitatively well predict the signals for modes $n = 2$ and 4 in absence of reflections on the floor. A difference is that the measured modulation of the amplitude of the signals is deeper than the predicted modulation. For higher modes $n = 4$ and 5 we observe more modulations than predicted by theory.

We attempted to obtain a better prediction by assuming different monopole strength or modify the monopole positions. A difference in monopole strength is not impossible as we do not have necessarily a pure standing wave in the tube. A difference in monopole strength did not fully explain the observed difference between theory and experiments, We only show results of theory assuming two equal monopole strength. Furthermore the experiments with inverted Hummer did not show important differences compared to the results with normal Hummer position (Fig. 8). The most important difference between theory and experi-

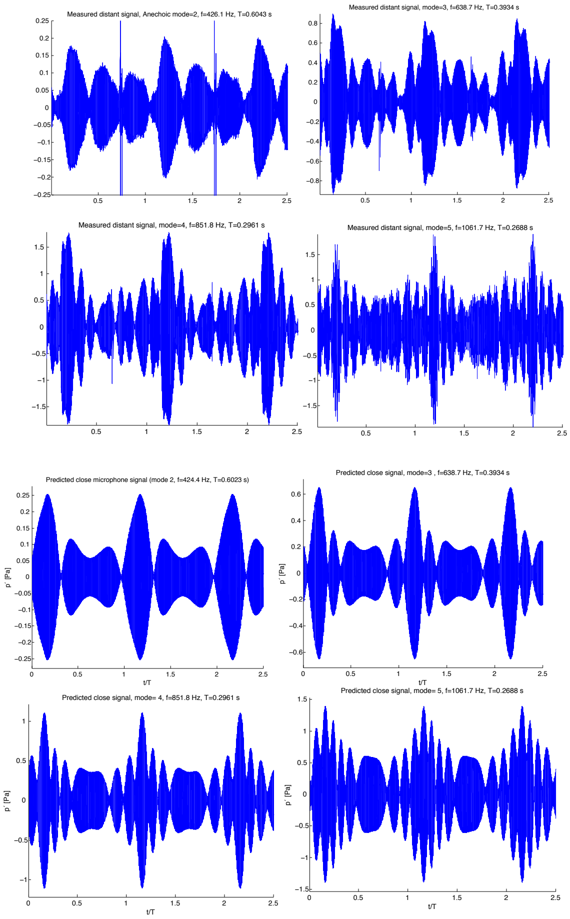

Figure 5. Close microphone signals as function of $t/T = tf$ for non-reflecting floor: experiment (four upper traces) and theory (four lower traces). In each block (experiment and theory) we have mode $n = 2$ at the upper left, $n = 3$ upper right, $n = 4$ lower left and $n = 5$ lower right. We observe the strange behavior of the signal for $n = 3$, which is expected to be due to resonant reflections by the table around 630 Hz..

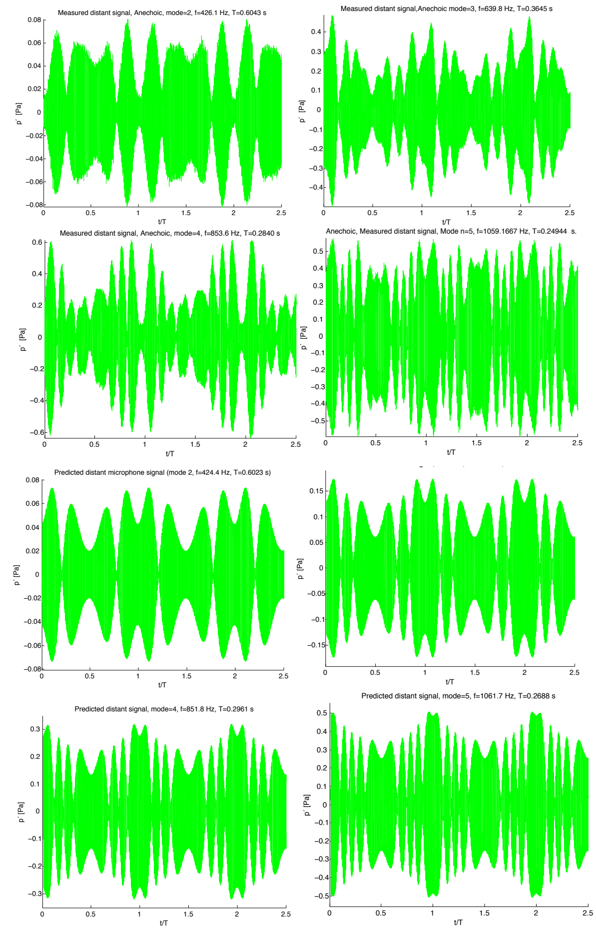

Figure 6. Distant microphone signals as function of $t/T = tf$ for non-reflecting floor: experiment (four upper traces) and theory (four lower traces). In each block (experiment and theory) we have mode $n = 2$ at the upper left, $n = 3$ upper right, $n = 4$ lower left and $n = 5$ lower right.The modulation of the measured signal is stronger than of the predicted signal.

ments, is the deeper modulation of the amplitude observed in the experiments. This modulation is dominated by the interference between the sources. This effect depends critically on the distance between the two sources compared to the acoustic wave length. A distance of exactly an integer number of half wave length would induce much stronger modulations than a shorter distance. As $c_{eff} < c_0$ we do expect a shorter distance. Furthermore the drag force of the flow around the pipe will bend the pipe reducing further the distance between the two sources. We therefore do not understand the observed deeper modulation. In Fig. 9 we show the measured signals of the distant microphone for a reflecting floor. The signals of the close microphone, which are not significantly affected by the reflections on the floor are not shown. The reflections on the floor increase the complexity of the observed signals. In view of the significant effect of reflections on the signal one should consider further the possible influence of the rods supporting the wheel on the measured signal (especially in the case of a non-reflecting floor).

5. MECHANICAL EFFECT

We now consider two mechanical effects.

It was argued by Hartman [10] that a flattening of the pitch can be observed upon increase of the whistling mode of the Hummer. This was explained as a result of the increase in pipe length due to the centrifugal force. Nice stable loud whistling was found for: $f_2 = 426.3$ Hz, $f_3 = 635.7$ Hz, $f_4 = 851.1$ Hz and $f_5 = 1061,5$ Hz. We have: $2f_3/(3f_2) = 0.994$, $f_4/(2f_2) = 0.998$ and $2f_5/(5f_2) = 0.996$, so that within the measurement accuracy we do not observe any flattening. Hanging a 1.2 kg weight to the pipe corresponding to the centrifugal force for $n = 5$ we only observed an elongation of 4 ± 1 mm, which is indeed negligible compared to the pipe length ($L = 750$ mm). A flattening in pitch of 5% (corresponding to an elongation of 4 cm) as reported by [10], [13] is expected to be due

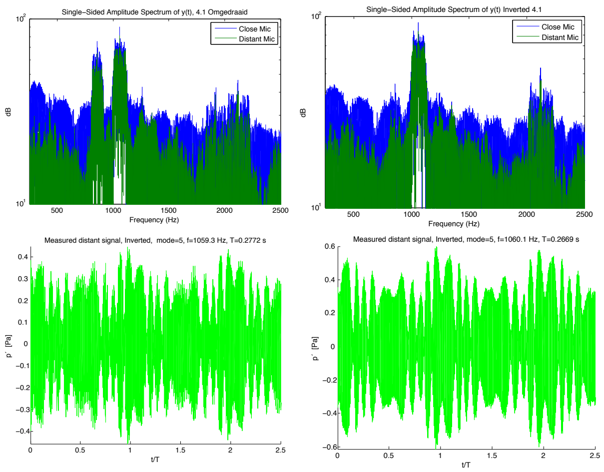

Figure 7. Left: Spectrum and distant signal p' for $n = 5$ showing the coexistence with the $n = 4$ mode. Right: same for stable $n = 5$ mode.

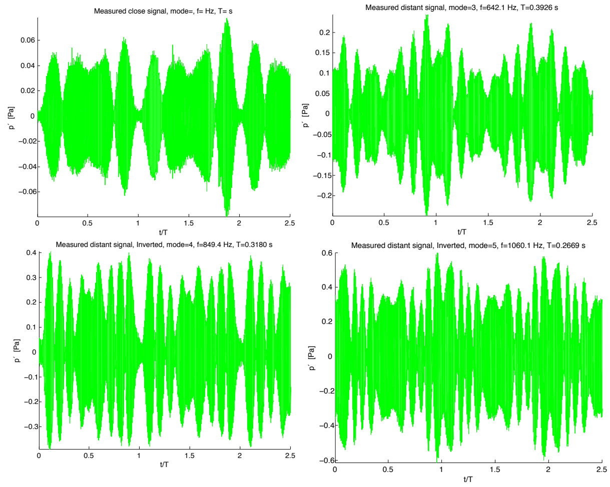

Figure 8. Distant microphone signals p' for inverted pipe: $n = 2$ (upper left), $n = 3$ (upper right),$n = 4$ (lower left) and $n = 5$ (lower left) for non-reflecting floor as functions of t/T.

to a larger flexibility of the pipe used in Hartman's experiments. Also the way our pipe is fixed to the wheel can reduce the elongation due to centrifugal acceleration.

Some of the deviations between theory and experiments could be due to transversal oscillation of the free pipe end driven by vortex shedding in the wake of the rotating pipe. The Von Karman vortex shedding frequency f_{VK} corresponds to a Strouhal number $Sr_D = 0.2$ based on the outer diameter of the pipe $D_{outer} = 33$ mm:

$$f_{VK} = 0.2 \frac{\Omega R_2}{D_{outer}} \tag{8}$$

For $n = 3$ we find $f_{VK} = 60$Hz. Assuming a clamped beam, we find for the first pipe bending mode for the pipe segment outside the wheel [12]:

$$f_0 = 0.55966 \sqrt{\frac{EI}{(R_2 - R_w)^4 \rho}} \tag{9}$$

We measured $EI = 0.62$ kg m^{3}s^{-2} by bending the pipe statically. We measured the pipe weight per unit length and found $\rho = 0.065$ kg m^{-1}. We find $f = 11$ Hz . The next mechanical resonance of a clamped beam is $6.267 f_0$. This would correspond to 70Hz, which is not far from the Von Karman vortex shedding frequency. Hence we cannot exclude significant flow induced vibration of the pipe due to vortex shedding. Such vibration would result into vertical oscillation. Note that the assumption of a clamped beam is not accurate. We furthermore do observed on video pictures of the experiments oscillations of the tip of the pipe. So a more careful study should be carried out.

In the case of a Hummer driven by hand the mechanical resonance modes are very low, so that we do not expect such a flow induced vibration. However one very clearly observes that the acceleration of the pipe by the movement of the hand induces bending traveling waves along the tube. Hence a model assuming a simple uniform rotation speed of the pipe termination is certainly not accurate.

6. CONCLUSIONS

Measurements of the sound radiated by a mechanically driven Hummer demonstrate that a simple theory assuming the radiation of two equally strong monopoles (in phase or opposite phase depending on the acoustic mode) explains most of the amplitude modulation of the sound radiated by a Hummer in an anechoic environment. While theory explains qualitatively the observed signal, it does not predict the depth of the modulations observed in the experiments.

Reflections on a floor or wall dramatically increase the complexity of the signal. We therefore suspect the reflections to be an important cause of deviation between theory and experiment. One cannot for example exclude that part of the deviation between theory and experiment is due to the reflections or diffraction of the sound on the rods supporting the set-up.

Experiments with modified pipe terminations (inverted Hummer or Hummer without horn) did not show a dramatic difference with the original measurements. A slight decrease in amplitude was observed due to the increased convective inlet losses.

For the highest mode which could be reached $n = 5$ we observe in some experiments a stable coexistence with mode $n = 4$. This contradicts the assumption that the non-linearity, needed to stabilize whistling, precludes the coexistence of self-sustained oscillations of two acoustic modes (non-harmonically related frequencies).

The model ignores the mechanical deformation of the Hummer. The reported flattening of the pitch [10], due to pipe elongation upon increase of pipe rotation speed, is not observed in our experiments.

Flow induces oscillation of the free pipe termination cannot be excluded and should be considered in a more accurate model of the Mechanical Dragon. Traveling bending waves induced by periodic impulses of the hand should be considered in the modeling of the hand driven Hummer.

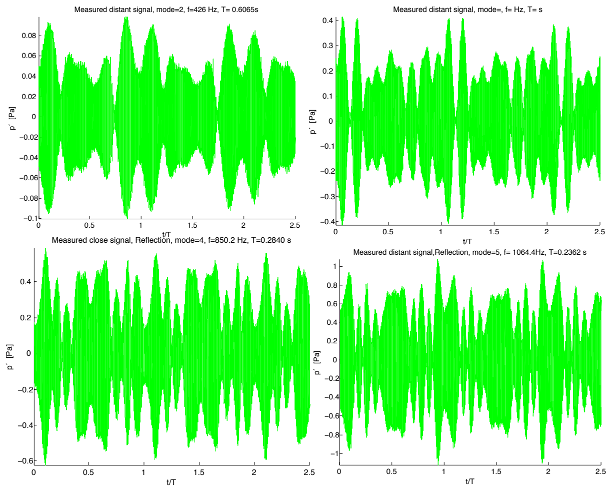

Figure 9. Distant microphone signals p' for inverted pipe: $n = 2$ (upper left), $n = 3$ (upper right),$n = 4$ (lower left) and $n = 5$ (lower left) for reflecting floor as functions of t/T.

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