# Part 1: Serra's Analysis

In this notebook we demonstrate our implementation of Serra's Sine Plus Noise analysis.

**Set the paths below to point to the directories of the Philharmonia Cello and Guitar samples.**

In [2]:
```
%matplotlib inline
%load_ext autoreload
%autoreload 2
from pathlib import Path
CELLO_PATH  = Path("/home/lukas/BA/philharmonia-samples/cello")
GUITAR_PATH = Path("/home/lukas/BA/philharmonia-samples/guitar")

# Output directories for figures and wavfiles
GFX_PATH    = Path("/home/lukas/BA/report/gfx/")
WAVS_PATH   = Path("/home/lukas/BA/report/wavs/")

# Whether to rebuild the dataset (The dataset needs to be built
# at least once. Building from the commandline seems to be
# significantly faster than from Jupyter, though I don't know why.
# So I advise to set this to False and build from the commandline
# instead.)
REBUILD_DATASETS = False
```

```
The autoreload extension is already loaded. To reload it, use:
  %reload_ext autoreload
```

In [3]:
```
%%capture

import pya
aserver = pya.Aserver()
aserver.boot()
pya.Aserver.default = aserver
```

```
ALSA lib pcm_dmix.c:1090:(snd_pcm_dmix_open) unable to open slave
ALSA lib pcm.c:2660:(snd_pcm_open_noupdate) Unknown PCM cards.pcm.rear
ALSA lib pcm.c:2660:(snd_pcm_open_noupdate) Unknown PCM cards.pcm.center_lfe
ALSA lib pcm.c:2660:(snd_pcm_open_noupdate) Unknown PCM cards.pcm.side
ALSA lib pcm_route.c:877:(find_matching_chmap) Found no matching channel map
ALSA lib dlmisc.c:345:(snd_dlobj_cache_get0) Cannot open shared library libasound_module_rate_samplerate.so (libaso
und_module_rate_samplerate.so: libasound_module_rate_samplerate.so: cannot open shared object file: No such file or
directory)
ALSA lib pcm_rate.c:1468:(snd_pcm_rate_open) Cannot find rate converter
connect(2) call to /dev/shm/jack-1000/default/jack_0 failed (err=No such file or directory)
attempt to connect to server failed
connect(2) call to /dev/shm/jack-1000/default/jack_0 failed (err=No such file or directory)
attempt to connect to server failed
ALSA lib pcm_oss.c:397:(_snd_pcm_oss_open) Cannot open device /dev/dsp
ALSA lib pcm_oss.c:397:(_snd_pcm_oss_open) Cannot open device /dev/dsp
ALSA lib dlmisc.c:345:(snd_dlobj_cache_get0) Cannot open shared library libasound_module_pcm_pipewire.so (libasound
_module_pcm_pipewire.so: libasound_module_pcm_pipewire.so: cannot open shared object file: No such file or director
y)
ALSA lib dlmisc.c:345:(snd_dlobj_cache_get0) Cannot open shared library libasound_module_pcm_pipewire.so (libasound
_module_pcm_pipewire.so: libasound_module_pcm_pipewire.so: cannot open shared object file: No such file or director
y)
ALSA lib pcm_a52.c:823:(_snd_pcm_a52_open) a52 is only for playback
ALSA lib dlmisc.c:345:(snd_dlobj_cache_get0) Cannot open shared library libasound_module_pcm_speex.so (libasound_mo
dule_pcm_speex.so: libasound_module_pcm_speex.so: cannot open shared object file: No such file or directory)
ALSA lib dlmisc.c:345:(snd_dlobj_cache_get0) Cannot open shared library libasound_module_pcm_speex.so (libasound_mo
dule_pcm_speex.so: libasound_module_pcm_speex.so: cannot open shared object file: No such file or directory)
ALSA lib pcm_usb_stream.c:486:(_snd_pcm_usb_stream_open) Invalid type for card
ALSA lib pcm_usb_stream.c:486:(_snd_pcm_usb_stream_open) Invalid type for card
ALSA lib pcm_dmix.c:1090:(snd_pcm_dmix_open) unable to open slave
```

In [4]:
```
# Initialization
import numpy as np
import matplotlib
import matplotlib.pyplot as plt
import pandas as pd

import principal_harmonics as ph

for path in [GFX_PATH, WAVS_PATH]:
    if path.exists() and not path.is_dir():
        raise NotADirectoryError(path)
    if not path.exists():
        path.mkdir()
```

```
ALSA lib pcm.c:8545:(snd_pcm_recover) underrun occurred
ALSA lib pcm.c:8545:(snd_pcm_recover) underrun occurred
ALSA lib pcm.c:8545:(snd_pcm_recover) underrun occurred
```

# Pitch estimation

The YIN Pitch tracker provides reliable pitch estimates for loud parts of the signal. For quiter parts, the estimation tends to jump - this is especially problematic for the guitar, where the signal decays rapidly.

- Use `principal_harmonics.pvoc.get_pitch()` to get the YIN pitch estimate of a signal
- Use `principal_harmonics.pvoc.constant_pitch()` to get a weighted-median estimate of a constant pitch given a time-varying pitch estimate and an expected frequency.

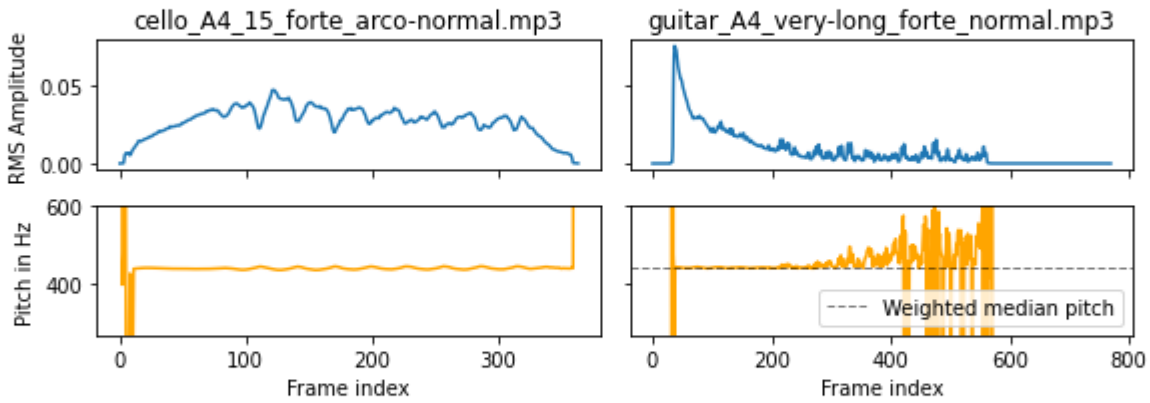
In [5]:

```
cello_path  = CELLO_PATH / 'cello_A4_15_forte_arco-normal.mp3'
guitar_path = GUITAR_PATH / 'guitar_A4_very-long_forte_normal.mp3'
cello_asig  = pya.Asig(str(cello_path))
guitar_asig = pya.Asig(str(guitar_path))
cello_pitch  = ph.pvoc.get_pitch(cello_asig)
guitar_pitch = ph.pvoc.get_pitch(guitar_asig)
constant_guitar_pitch = ph.pvoc.constant_pitch(guitar_pitch, expected=440.0)
```

In [6]:

```
fig, ((cello_rms_ax, guitar_rms_ax), (cello_pitch_ax, guitar_pitch_ax)) = \
    plt.subplots(nrows=2, ncols=2, sharex='col', sharey='row', figsize=(8.2, 3))

plt.sca(cello_rms_ax)
cello_asig.window_op(fn='rms', nperseg=512, stride=256).plot(x_as_time=False, label='RMS amplitude')
cello_rms_ax.set_ylabel("RMS Amplitude")
cello_rms_ax.set_title(cello_path.name)

cello_pitch_ax.plot(cello_pitch, label='YIN pitch estimation', c='orange')
cello_pitch_ax.set_ylabel("Pitch in Hz")
cello_pitch_ax.set_ylim(270, 600)
cello_pitch_ax.set_xlabel("Frame index")

plt.sca(guitar_rms_ax)
guitar_asig.window_op(fn='rms', nperseg=512, stride=256).plot(x_as_time=False, label='RMS amplitude')
guitar_rms_ax.set_title(guitar_path.name)

guitar_pitch_ax.plot(guitar_pitch,  c='orange')
guitar_pitch_ax.set_xlabel("Frame index")
guitar_pitch_ax.axhline(constant_guitar_pitch, linestyle='--', linewidth=1, c='black', label='Weighted median pitch
guitar_pitch_ax.legend(loc=4)

fig.tight_layout()

plt.savefig(GFX_PATH / '1-pitch-estimation.eps')
```

```
The PostScript backend does not support transparency; partially transparent artists will be rendered opaque.
```




# Sinusoidal analysis

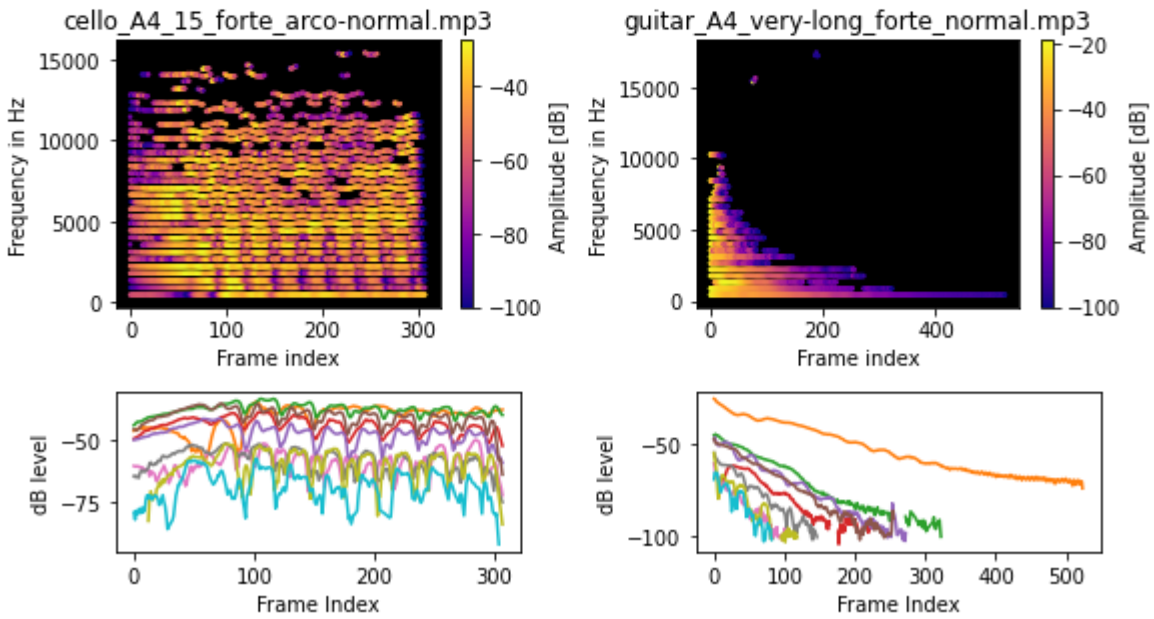
Let us analyze a single sample using the sinusoidal analysis. We visualize the timbre vectors in two different ways:

*Plotting the detected peak frequencies vs. time.* The color denotes the decibel-scaled amplitude of the peak. This can give a holistic view of the structure of the deterministic component we extracted, including vibrato, jumping partials, missing values, etc. We can use this to judge the overall performance of the analysis and to tune analysis parameters to the data at hand. However, we cannot identify finer structures in the trajectory of the peak amplitudes. *Plotting (a subset) of the detected peak amplitudes vs time*, we can better observe the behaviour of the overtone amplitudes.

In [7]:
```
# using simple peak matching (default)
cello_pitch = ph.pvoc.get_pitch(cello_asig)
cello_freqs, cello_coefs = ph.pvoc.sinusoidal_analysis(cello_asig, cello_pitch)
start, stop = ph.pvoc.ClipStationary().clip(cello_coefs)
cello_freqs, cello_coefs = cello_freqs[start:stop], cello_coefs[start:stop]

cello_asig_clipped = cello_asig[start*256:stop*256] # we'll need this for later...

# ... and using tracking peak matching
cello_freqs_tracking, cello_coefs_tracking = ph.pvoc.sinusoidal_analysis(cello_asig, cello_pitch, peak_matching='tr
cello_freqs_tracking, cello_coefs_tracking = cello_freqs_tracking[start:stop], cello_coefs_tracking[start:stop]

# using simple peak matching (default)
guitar_pitch = ph.pvoc.constant_pitch(ph.pvoc.get_pitch(guitar_asig), expected=440.0)
guitar_freqs, guitar_coefs = ph.pvoc.sinusoidal_analysis(guitar_asig, guitar_pitch)
start, stop = ph.pvoc.ClipTransient().clip(guitar_coefs)
guitar_freqs, guitar_coefs = guitar_freqs[start:stop], guitar_coefs[start:stop]
```

In [8]:
```
fig = plt.figure(figsize=(8.2, 4.5))

gs = matplotlib.gridspec.GridSpec(2, 2, height_ratios=[0.5, 0.3])
ax = fig.add_subplot(gs[0,0])
plt.sca(ax)
plt.title(cello_path.name)
ph.plots.plot_timbre_vectors(cello_freqs, cello_coefs)

ax = fig.add_subplot(gs[0,1])
plt.sca(ax)
plt.title(guitar_path.name)
ph.plots.plot_timbre_vectors(guitar_freqs, guitar_coefs)

ax = fig.add_subplot(gs[1,0])
plt.sca(ax)
ph.plots.plot_ampls(np.abs(cello_coefs[:, :10]), dbify=True, write_numbers=False)
plt.xlabel("Frame Index")
ax = fig.add_subplot(gs[1,1])
plt.sca(ax)
ph.plots.plot_ampls(np.abs(guitar_coefs[:, :10]), dbify=True, write_numbers=False)
plt.xlabel("Frame Index")

plt.tight_layout()
plt.savefig(GFX_PATH / '1-timbre-vectors.png', dpi=300)
```

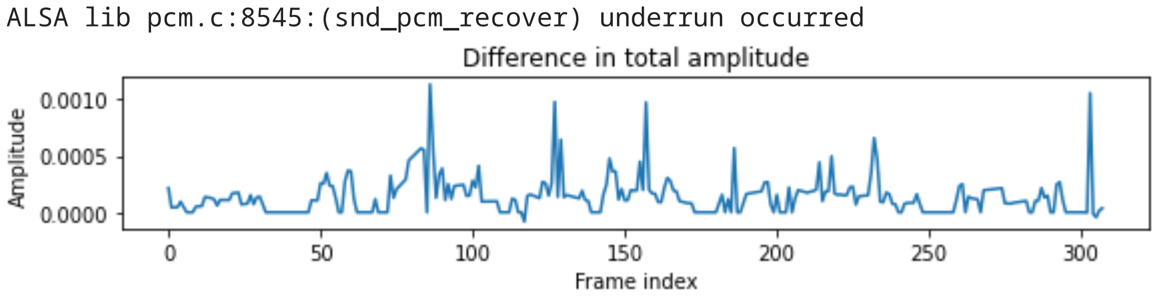
```
/home/lukas/miniconda3/envs/ba-venv/lib/python3.9/site-packages/pya/helper/helpers.py:55: RuntimeWarning: divide by
zero encountered in log10
  return 20 * np.log10(amp)
```




Comparing the performance of the simple and tracking peak matchers, we see little difference in extracted amplitude.

In [9]:
```
plt.figure(figsize=(8.2, 2))
plt.title("Difference in total amplitude")
plt.xlabel("Frame index")
plt.ylabel("Amplitude")
cello_ampls_simple   = np.nansum(np.abs(cello_coefs), axis=1)
cello_ampls_tracking = np.nansum(np.abs(cello_coefs_tracking), axis=1)
plt.plot(cello_ampls_simple - cello_ampls_tracking)

plt.tight_layout()
plt.savefig(GFX_PATH / "1-peak-matching-eval.eps")
```

```
ALSA lib pcm.c:8545:(snd_pcm_recover) underrun occurred
```

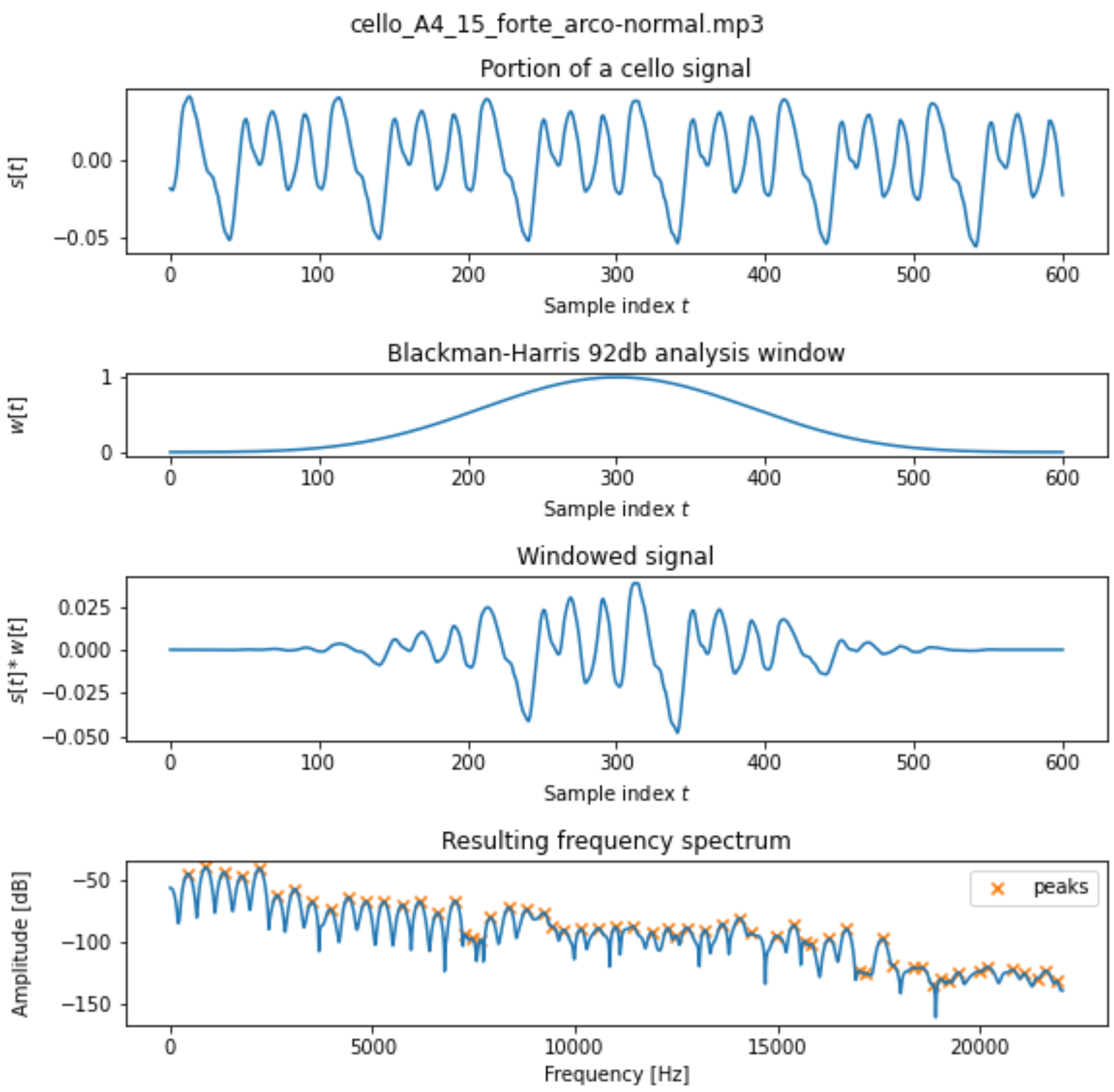


We can analyze the inner workings of the analysis by having it return the spectrum computation for each frame...

In [10]:
```
freqs, coefs, steps = ph.pvoc.sinusoidal_analysis(cello_asig, cello_pitch, return_steps=True)
step = steps[42]
```

In [11]:
```
%matplotlib inline
import scipy.signal
import matplotlib.gridspec

fig = plt.figure(figsize=(8.2, 8))
gs = matplotlib.gridspec.GridSpec(4, 1, height_ratios=[1,0.5,1,1])
plt.suptitle(cello_path.name)

ax = fig.add_subplot(gs[0, 0])
step.asig_slice.plot(x_as_time=False, ax=ax)
ax.set_title("Portion of a cello signal")
ax.set_xlabel("Sample index $t$")
ax.set_ylabel("$s[t]$")

ax = fig.add_subplot(gs[1, 0])
win = scipy.signal.get_window('blackmanharris', step.asig_slice.samples)
ax.plot(win)
ax.set_title("Blackman-Harris 92db analysis window")
ax.set_xlabel("Sample index $t$")
ax.set_ylabel("$w[t]$")

ax = fig.add_subplot(gs[2, 0])
(step.asig_slice * win).plot(x_as_time=False, ax=ax)
ax.set_title("Windowed signal")
ax.set_xlabel("Sample index $t$")
ax.set_ylabel("$s[t] * w[t]$")

ax = fig.add_subplot(gs[3, 0])
fft_freqs = step.fft_freqs
fft_dbs   = pya.ampdb(np.abs(step.fft_coefs))
ax.plot(step.fft_freqs, fft_dbs)

maxs = scipy.signal.argrelmax(fft_dbs)
ax.scatter(fft_freqs[maxs], fft_dbs[maxs], marker='x', label='peaks', color='tab:orange')

ax.set_ylabel("Amplitude [dB]")
ax.set_xlabel("Frequency [Hz]")
ax.legend()
ax.set_title("Resulting frequency spectrum")

fig.align_ylabels()
plt.tight_layout()

plt.savefig(GFX_PATH / "1-spectrum.eps")
```

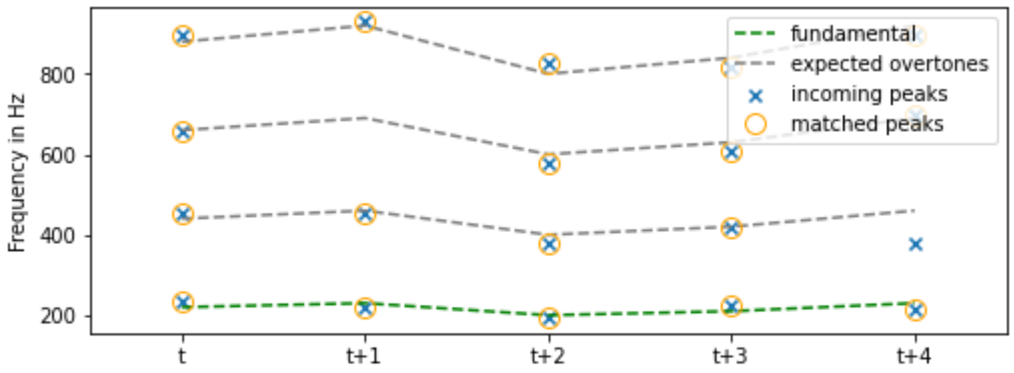
```
The PostScript backend does not support transparency; partially transparent artists will be rendered opaque.
```




This figure illustrates the simple peak matcher. (Not used in the report)

In [12]:
```
import matplotlib.gridspec as gridspec
import matplotlib.image as img
rng = np.random.default_rng(seed=42)

plt.figure(figsize=(8.2, 3))
fundamentals    = np.array([220, 230, 200, 210, 230])
n               = fundamentals.shape[0]
ks              = np.arange(1, 5).reshape((1, -1))
m               = ks.shape[1]
expected_freqs = fundamentals.reshape((-1, 1)) * ks
devs            = np.random.uniform(-30, 30, size=expected_freqs.shape)
devs[1, 2] = np.nan
devs[4, 1] = -80
actual_freqs    = expected_freqs + devs

xs = np.broadcast_to(np.arange(n).reshape((-1, 1)), actual_freqs.shape)

plt.ylabel("Frequency in Hz")
plt.xlim(-0.5, n - 0.5)
plt.xticks(np.arange(n), labels=['t', 't+1', 't+2', 't+3', 't+4'])

plt.plot(np.arange(n), fundamentals, label='fundamental', c='green', linestyle='--')
for i in range(1, m):
    line = plt.plot(xs[:, i], expected_freqs[:, i],  c='gray', linestyle='--')[0]
    if i == 1:
        line.set_label('expected overtones')

plt.scatter(xs.ravel(), actual_freqs.ravel(), label='incoming peaks', marker='x')
matches = np.where(np.abs(expected_freqs - actual_freqs) < 30)
plt.plot(xs[matches].ravel(), actual_freqs[matches].ravel(), c='orange', marker='o', markersize=10, label='matched p

plt.legend(loc=1)
plt.savefig(GFX_PATH / '1-expected-overtone-peak-matcher.eps')
```

The PostScript backend does not support transparency; partially transparent artists will be rendered opaque.

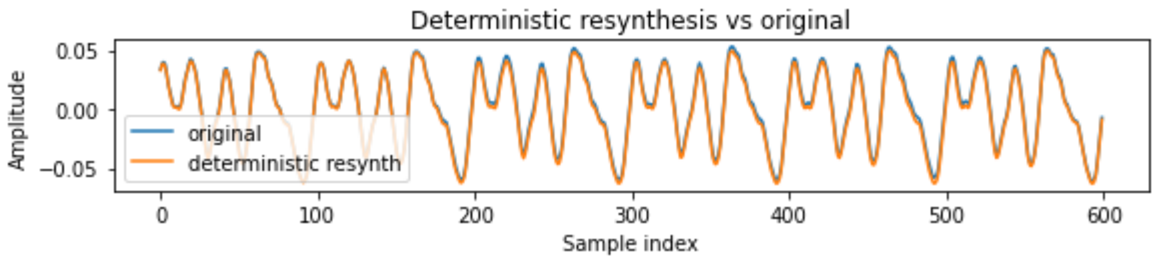



Having gathered timbre vectors, let's check that the resynthesis worked:

In [13]:
```
resynth = ph.pvoc.phase_correct_resynth(cello_freqs, cello_coefs)
```

In [14]:
```
plt.figure(figsize=(8.2, 2))
plt.title("Deterministic resynthesis vs original")
plt.ylabel("Amplitude")
t = 42*256
n = int((6*step.n_samples)//2)
cello_asig_clipped[t-n : t+n].plot(label='original', x_as_time=False)
resynth[t-n:t+n].plot(label='deterministic resynth', x_as_time=False)
plt.xlabel("Sample index")
plt.legend(loc=0)

plt.tight_layout()
plt.savefig(GFX_PATH / '1-phase-correct-resynth.eps')
```

The PostScript backend does not support transparency; partially transparent artists will be rendered opaque.




We can subtract the synthesized signal from the original to get the stochastic residue.

In [15]:
```
guitar_freqs_tracking, guitar_coefs_tracking = ph.pvoc.sinusoidal_analysis(guitar_asig, guitar_pitch, peak_matching=
guitar_resynth = ph.pvoc.phase_correct_resynth(guitar_freqs_tracking, guitar_coefs_tracking)
(guitar_resynth.x - guitar_asig.x).play()
```

Out[15]:
```
Asig('_subtracted'): 1 x 197120 @ 44100Hz = 4.470s cn=['0']
```

Using plain additive synthesis without considering the phases, we get a signal that is perceptually the same.

In [16]:
```
guitar_resynth_additive = ph.pvoc.additive_resynth(guitar_freqs_tracking, np.abs(guitar_coefs_tracking))
guitar_resynth_additive.play()
```

```
(1, 1) (770, 40) (770, 40)
ALSA lib pcm.c:8545:(snd_pcm_recover) underrun occurred
```

Out[16]:

```
Asig(''): 1 x 196864 @ 44100Hz = 4.464s cn=['0']
```

# Building the dataset

Having looked at the analysis of single samples, let us now build the whole dataset. If `REBUILD_DATASET` was set to True, this might take a while.

In [17]:

```
if REBUILD_DATASETS:
    for path in [CELLO_PATH, GUITAR_PATH]:
        # delete labels file if it exists
        if (path / 'labels.csv').exists():
            (path / 'labels.csv').unlink()
    ph.dataset.build_labels(base_dir=CELLO_PATH,  glob='cello_*_15_*_arco-normal.mp3', parser='philharmonia')
    ph.dataset.build_labels(base_dir=GUITAR_PATH, glob='guitar_*_very-long_*_normal.mp3', parser='philharmonia')

    ph.dataset.build_dataset(GUITAR_PATH, pitch_mode='constant', clip_strategy='transient')
    ph.dataset.build_dataset(CELLO_PATH,  pitch_mode='variable', clip_strategy='stationary')
```

We can load the whole dataset from disk using `ph.dataset.open_dataset`. The dataframe that is returned contains all analysis results and the labels. Frequencies and Coefficients are stored as np.ndarray *objects*, i.e. they need to be unwrapped before they can be used for analysis in a pandas Series. This is because the analysis results might not have the same dimensionality (the stochastic analysis might have a different hop size than the deterministic analysis))

In [18]:

```
cello_df  = ph.dataset.open_dataset(CELLO_PATH)
guitar_df = ph.dataset.open_dataset(GUITAR_PATH)
pd.options.display.min_rows=30
pd.options.display.max_rows=30
cello_df
```

Out[18]:

| filename | Unnamed: 0 | midi | exclude | other | instrument | duration | dynamic | note | clipped_wav | resynth_wav | r |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **cello_A2_15_forte_arco-normal.mp3** | 0 | 45.0 | False | arco-normal | cello | 15 | forte | A2 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_A2_15_pianissimo_arco-normal.mp3** | 1 | 45.0 | False | arco-normal | cello | 15 | pianissimo | A2 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_A2_15_piano_arco-normal.mp3** | 2 | 45.0 | False | arco-normal | cello | 15 | piano | A2 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_A3_15_forte_arco-normal.mp3** | 3 | 57.0 | False | arco-normal | cello | 15 | forte | A3 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_A3_15_mezzo-piano_arco-normal.mp3** | 4 | 57.0 | False | arco-normal | cello | 15 | mezzo-piano | A3 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_A4_15_forte_arco-normal.mp3** | 5 | 69.0 | False | arco-normal | cello | 15 | forte | A4 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_A4_15_mezzo-piano_arco-normal.mp3** | 6 | 69.0 | False | arco-normal | cello | 15 | mezzo-piano | A4 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_A5_15_forte_arco-normal.mp3** | 7 | 81.0 | False | arco-normal | cello | 15 | forte | A5 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_A5_15_mezzo-piano_arco-normal.mp3** | 8 | 81.0 | False | arco-normal | cello | 15 | mezzo-piano | A5 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_A5_15_pianissimo_arco-normal.mp3** | 9 | 81.0 | False | arco-normal | cello | 15 | pianissimo | A5 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_As2_15_forte_arco-normal.mp3** | 10 | 46.0 | False | arco-normal | cello | 15 | forte | A♯2 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_As2_15_fortissimo_arco-normal.mp3** | 11 | 46.0 | False | arco-normal | cello | 15 | fortissimo | A♯2 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_As2_15_pianissimo_arco-normal.mp3** | 12 | 46.0 | False | arco-normal | cello | 15 | pianissimo | A♯2 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_As2_15_piano_arco-normal.mp3** | 13 | 46.0 | False | arco-normal | cello | 15 | piano | A♯2 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_As3_15_forte_arco-normal.mp3** | 14 | 58.0 | False | arco-normal | cello | 15 | forte | A♯3 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **...** | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | |
| **cello_Gs2_15_fortissimo_arco-normal.mp3** | 166 | 44.0 | False | arco-normal | cello | 15 | fortissimo | G♯2 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_Gs2_15_pianissimo_arco-normal.mp3** | 167 | 44.0 | False | arco-normal | cello | 15 | pianissimo | G♯2 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_Gs2_15_piano_arco-normal.mp3** | 168 | 44.0 | False | arco-normal | cello | 15 | piano | G♯2 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_Gs3_15_forte_arco-normal.mp3** | 169 | 56.0 | False | arco-normal | cello | 15 | forte | G♯3 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |

| | Unnamed: 0 | midi | exclude | other | instrument | duration | dynamic | note | clipped_wav | resynth_wav | r |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **filename** | | | | | | | | | | | |
| **cello_Gs3_15_fortissimo_arco-normal.mp3** | 170 | 56.0 | False | arco-normal | cello | 15 | fortissimo | G♯3 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_Gs3_15_pianissimo_arco-normal.mp3** | 171 | 56.0 | False | arco-normal | cello | 15 | pianissimo | G♯3 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_Gs3_15_piano_arco-normal.mp3** | 172 | 56.0 | False | arco-normal | cello | 15 | piano | G♯3 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_Gs4_15_forte_arco-normal.mp3** | 173 | 68.0 | False | arco-normal | cello | 15 | forte | G♯4 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_Gs4_15_fortissimo_arco-normal.mp3** | 174 | 68.0 | False | arco-normal | cello | 15 | fortissimo | G♯4 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_Gs4_15_mezzo-piano_arco-normal.mp3** | 175 | 68.0 | False | arco-normal | cello | 15 | mezzo-piano | G♯4 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_Gs4_15_pianissimo_arco-normal.mp3** | 176 | 68.0 | False | arco-normal | cello | 15 | pianissimo | G♯4 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_Gs5_15_forte_arco-normal.mp3** | 177 | 80.0 | False | arco-normal | cello | 15 | forte | G♯5 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_Gs5_15_fortissimo_arco-normal.mp3** | 178 | 80.0 | False | arco-normal | cello | 15 | fortissimo | G♯5 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_Gs5_15_mezzo-piano_arco-normal.mp3** | 179 | 80.0 | False | arco-normal | cello | 15 | mezzo-piano | G♯5 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |
| **cello_Gs5_15_pianissimo_arco-normal.mp3** | 180 | 80.0 | False | arco-normal | cello | 15 | pianissimo | G♯5 | /home/lukas /BA/philharmonia-samples/cello /cell... | /home/lukas /BA/philharmonia-samples/cello /cell... | /h /BA/phi sar |

181 rows × 16 columns

We can unwrap ndarrays by using `ph.dataset.expand_ndarrays()` , yielding a `MultiIndex` ed dataframe:

In [19]:
```
ph.dataset.expand_ndarrays(cello_df, ['freqs', 'coefs'])
```

Out[19]:

| filename | n | freqs-0 | freqs-1 | freqs-2 | freqs-3 | freqs-4 | freqs-5 | freqs-6 | freqs-7 | freqs |
|---|---|---|---|---|---|---|---|---|---|---|
| cello_A2_15_forte_arco-normal.mp3 | 0 | NaN | 104.137558 | 220.598289 | 318.077413 | NaN | 528.929370 | 635.073708 | 741.260676 | 848.03838 |
| | 1 | NaN | 104.147027 | 216.604819 | 319.800956 | NaN | 528.279552 | 638.403465 | 743.001433 | 849.11652 |
| | 2 | NaN | 104.319988 | 215.776632 | 321.678334 | NaN | 529.864419 | 640.562735 | 745.262760 | 850.35237 |
| | 3 | NaN | 104.724961 | 215.664823 | 323.746908 | 442.430948 | 533.007135 | 641.596162 | 749.592093 | 852.29140 |
| | 4 | NaN | 105.260677 | 216.328448 | 325.791948 | 440.828898 | 536.100527 | 642.077293 | 756.082938 | 854.95418 |
| | 5 | NaN | 105.572623 | 217.762039 | 327.478049 | 439.372924 | 538.714698 | 642.731984 | 762.984872 | 857.05224 |
| | 6 | NaN | 105.823635 | 219.582341 | 328.353235 | 439.457084 | 541.261270 | 643.852288 | 765.782298 | 858.11330 |
| | 7 | NaN | 106.518020 | 220.518023 | 328.042049 | 441.372627 | 543.214222 | 645.470405 | 761.970830 | 859.67437 |
| | 8 | NaN | 107.561063 | 220.101268 | 326.858993 | 442.859676 | 544.279501 | 647.537026 | 755.484977 | 862.08608 |
| | 9 | NaN | 108.587171 | 219.288079 | 325.775657 | 441.748662 | 544.841642 | 649.172645 | 756.678083 | 863.19765 |
| | 10 | NaN | 109.621103 | 218.927402 | 325.263526 | 439.400788 | 545.034300 | 649.124158 | 764.487761 | 862.68353 |
| | 11 | NaN | 110.476806 | 218.887618 | 325.374477 | 438.485908 | 544.778753 | 648.301910 | 770.963124 | 861.93363 |
| | 12 | NaN | 110.710476 | 218.861005 | 325.714377 | 439.259736 | 544.406793 | 648.548954 | 758.970842 | 861.88556 |
| | 13 | NaN | 110.205722 | 218.821524 | 325.838015 | 440.156431 | 544.108501 | 650.280453 | 744.371597 | 862.52448 |
| | 14 | NaN | 109.388313 | 218.787805 | 325.903406 | 440.237244 | 543.966887 | 651.907194 | NaN | 863.18691 |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | |
| cello_Gs5_15_pianissimo_arco-normal.mp3 | 224 | NaN | 826.871125 | 1674.464250 | NaN | 3329.788233 | 4161.082620 | 4967.450000 | 5763.077669 | 6670.02495 |
| | 225 | NaN | 827.197457 | 1660.688193 | NaN | 3313.823610 | 4134.538414 | 4907.475654 | 5762.337811 | 6628.72063 |
| | 226 | NaN | 828.207768 | 1654.150380 | NaN | 3313.022546 | 4142.826831 | 5005.622510 | 5761.597952 | 6586.99151 |
| | 227 | NaN | 827.432263 | 1655.191645 | NaN | 3318.297161 | 4164.283833 | NaN | 5760.858094 | 6651.17151 |

| filename | n | freqs-0 | freqs-1 | freqs-2 | freqs-3 | freqs-4 | freqs-5 | freqs-6 | freqs-7 | freqs- |
|---|---|---|---|---|---|---|---|---|---|---|
| | 228 | NaN | 829.678140 | 1650.765588 | NaN | 3320.502648 | 4135.942630 | NaN | 5760.118236 | 6636.88464 |
| | 229 | NaN | 829.861801 | 1658.678979 | NaN | 3317.341215 | 4147.344627 | NaN | 5822.171627 | 6617.81116 |
| | 230 | NaN | 832.514302 | 1668.432379 | NaN | 3333.890426 | 4163.951625 | NaN | 5802.470982 | 6638.67744 |
| | 231 | NaN | 830.266029 | 1660.239430 | NaN | 3320.030134 | 4159.836821 | NaN | 5870.150936 | 6675.11936 |
| | 232 | NaN | 832.361679 | 1670.256452 | NaN | 3337.697085 | 4165.031531 | NaN | 5876.821312 | 6666.67858 |
| | 233 | NaN | 832.177705 | 1664.896523 | NaN | 3332.317098 | 4170.635537 | NaN | 5819.169078 | 6636.19170 |
| | 234 | NaN | 832.599091 | 1672.435802 | NaN | 3337.399565 | 4174.660442 | NaN | NaN | 6681.90450 |
| | 235 | NaN | 830.661842 | 1666.078569 | NaN | 3331.438144 | 4178.729425 | NaN | NaN | 6713.34786 |
| | 236 | NaN | 832.651638 | 1661.470263 | NaN | 3338.471721 | 4171.561577 | NaN | NaN | 6670.74008 |
| | 237 | NaN | 828.948936 | 1660.014666 | NaN | 3334.191989 | 4177.842297 | NaN | NaN | 6673.44022 |
| | 238 | NaN | 828.786480 | 1655.368995 | NaN | 3309.162089 | 4136.953845 | NaN | NaN | 6585.83736 |

55842 rows × 94 columns

Let's look at the results for the cello. Notice that the r2 scores are degraded only for C2, C#2, D2 notes.

In [20]:
```
cello_df.sort_values('harmonic_r2')[['note', 'harmonic_r2']]
```

Out[20]:

| | note | harmonic_r2 |
|---|---|---|
| **filename** | | |
| **cello_Cs2_15_fortissimo_arco-normal.mp3** | C#2 | 0.000184 |
| **cello_Cs2_15_piano_arco-normal.mp3** | C#2 | 0.000417 |
| **cello_Cs2_15_forte_arco-normal.mp3** | C#2 | 0.000643 |
| **cello_C2_15_piano_arco-normal.mp3** | C2 | 0.021169 |
| **cello_D2_15_pianissimo_arco-normal.mp3** | D2 | 0.022226 |
| **cello_C2_15_forte_arco-normal.mp3** | C2 | 0.109291 |
| **cello_D2_15_mezzo-piano_arco-normal.mp3** | D2 | 0.116769 |
| **cello_D2_15_forte_arco-normal.mp3** | D2 | 0.151544 |
| **cello_Cs2_15_pianissimo_arco-normal.mp3** | C#2 | 0.167291 |
| **cello_C2_15_fortissimo_arco-normal.mp3** | C2 | 0.368731 |
| **cello_C2_15_pianissimo_arco-normal.mp3** | C2 | 0.779312 |
| **cello_Ds2_15_fortissimo_arco-normal.mp3** | D#2 | 0.794196 |
| **cello_Ds2_15_piano_arco-normal.mp3** | D#2 | 0.834249 |
| **cello_Ds2_15_forte_arco-normal.mp3** | D#2 | 0.852125 |
| **cello_Ds2_15_pianissimo_arco-normal.mp3** | D#2 | 0.885786 |
| **...** | ... | ... |
| **cello_Fs3_15_fortissimo_arco-normal.mp3** | F#3 | 0.998054 |
| **cello_Gs3_15_forte_arco-normal.mp3** | G#3 | 0.998054 |
| **cello_Gs2_15_forte_arco-normal.mp3** | G#2 | 0.998257 |
| **cello_Ds4_15_mezzo-piano_arco-normal.mp3** | D#4 | 0.998317 |
| **cello_F3_15_piano_arco-normal.mp3** | F3 | 0.998342 |
| **cello_E3_15_forte_arco-normal.mp3** | E3 | 0.998353 |
| **cello_Ds3_15_forte_arco-normal.mp3** | D#3 | 0.998408 |
| **cello_Ds3_15_fortissimo_arco-normal.mp3** | D#3 | 0.998559 |
| **cello_E3_15_fortissimo_arco-normal.mp3** | E3 | 0.998592 |
| **cello_Ds4_15_forte_arco-normal.mp3** | D#4 | 0.998685 |
| **cello_F2_15_piano_arco-normal.mp3** | F2 | 0.998764 |
| **cello_Fs3_15_forte_arco-normal.mp3** | F#3 | 0.998830 |
| **cello_F2_15_forte_arco-normal.mp3** | F2 | 0.999023 |
| **cello_F3_15_forte_arco-normal.mp3** | F3 | 0.999042 |
| **cello_F3_15_fortissimo_arco-normal.mp3** | F3 | 0.999061 |

181 rows × 2 columns

The guitar shows worse R2 results. However, notice that the samples with the worst R2 scores are almost all `piano` samples, and the samples with the best scores are almost all `forte` samples.

In [21]:

```
guitar_df.sort_values('harmonic_r2')[['note', 'harmonic_r2']]
```

Out[21]:

| filename | note | harmonic_r2 |
|---|---|---|
| guitar_E5_very-long_piano_normal.mp3 | E5 | 0.198769 |
| guitar_E2_very-long_piano_normal.mp3 | E2 | 0.239426 |
| guitar_Ds5_very-long_piano_normal.mp3 | D♯5 | 0.249378 |
| guitar_Gs5_very-long_forte_normal.mp3 | G♯5 | 0.268161 |
| guitar_C3_very-long_piano_normal.mp3 | C3 | 0.312250 |
| guitar_F3_very-long_piano_normal.mp3 | F3 | 0.322729 |
| guitar_E3_very-long_piano_normal.mp3 | E3 | 0.336654 |
| guitar_G4_very-long_piano_normal.mp3 | G4 | 0.395874 |
| guitar_Cs3_very-long_piano_normal.mp3 | C♯3 | 0.405350 |
| guitar_Ds5_very-long_forte_normal.mp3 | D♯5 | 0.425177 |
| guitar_B2_very-long_piano_normal.mp3 | B2 | 0.429724 |
| guitar_G5_very-long_forte_normal.mp3 | G5 | 0.455253 |
| guitar_Fs3_very-long_piano_normal.mp3 | F♯3 | 0.495844 |
| guitar_D3_very-long_piano_normal.mp3 | D3 | 0.504071 |
| guitar_Ds3_very-long_piano_normal.mp3 | D♯3 | 0.519614 |
| ... | ... | ... |
| guitar_Fs3_very-long_forte_normal.mp3 | F♯3 | 0.879171 |
| guitar_A4_very-long_forte_normal.mp3 | A4 | 0.881476 |
| guitar_D5_very-long_forte_normal.mp3 | D5 | 0.891243 |
| guitar_As3_very-long_piano_normal.mp3 | A♯3 | 0.895590 |
| guitar_As2_very-long_forte_normal.mp3 | A♯2 | 0.900786 |
| guitar_F3_very-long_forte_normal.mp3 | F3 | 0.903941 |
| guitar_Gs3_very-long_forte_normal.mp3 | G♯3 | 0.906259 |
| guitar_Ds3_very-long_forte_normal.mp3 | D♯3 | 0.910498 |
| guitar_B2_very-long_forte_normal.mp3 | B2 | 0.910852 |
| guitar_D3_very-long_forte_normal.mp3 | D3 | 0.917608 |
| guitar_C6_very-long_piano_normal.mp3 | C6 | 0.928321 |
| guitar_A3_very-long_forte_normal.mp3 | A3 | 0.929812 |
| guitar_B3_very-long_forte_normal.mp3 | B3 | 0.939934 |
| guitar_G2_very-long_forte_normal.mp3 | G2 | 0.957464 |
| guitar_As3_very-long_forte_normal.mp3 | A♯3 | 0.958670 |

71 rows × 2 columns

If we interpret the dynamic as `piano == 0` and `forte == 1`, we get a 0.52 corellation between the dynamic and the r2 score.

In [22]:

```
guitar_df['dynamic_int'] = guitar_df.dynamic.apply(lambda d: 1.0 if d == 'forte' else 0)
guitar_df.convert_dtypes()[['dynamic_int', 'harmonic_r2']].corr()
```

Out[22]:

| | dynamic_int | harmonic_r2 |
|---|---|---|
| dynamic_int | 1.000000 | 0.518304 |
| harmonic_r2 | 0.518304 | 1.000000 |

Let's build all stats for the report:

In [23]:
```
import librosa

quantiles = [0, 0.25, 0.5, 0.75, 1]
cello_r2s          = cello_df.harmonic_r2.quantile(quantiles)
cello_over_d2_r2s = cello_df[cello_df.midi > librosa.note_to_midi('D2')].harmonic_r2.quantile(quantiles)

guitar_r2s       = guitar_df.harmonic_r2.quantile(quantiles)
guitar_piano_r2s = guitar_df[guitar_df.dynamic == 'piano'].harmonic_r2.quantile(quantiles)
guitar_forte_r2s = guitar_df[guitar_df.dynamic == 'forte'].harmonic_r2.quantile(quantiles)

r2_stats = pd.DataFrame(
    [
        cello_r2s,
        cello_over_d2_r2s,
        guitar_r2s,
        guitar_piano_r2s,
        guitar_forte_r2s
    ],
    index=['Cello',
           '  Cello > D2',
           'Guitar',
           r'  Guitar \textbf{\textit{p}}',
           r'  Guitar \textbf{\textit{f}}']
)
r2_stats.columns = [r'\(q=0\) (min)', r'\(q=0.25\)', r'\(q=0.5\) (median)',
                    r'\(q=0.75\)', r'\(q=1\) (max)']
r2_stats
```

Out[23]:

| | $q=0$ (min) | $q = 0.25$ | $q=0.5$ (median) | $q = 0.75$ | $q=1$ (max) |
|---|---|---|---|---|---|
| Cello | 0.000184 | 0.978829 | 0.991228 | 0.996171 | 0.999061 |
| Cello > D2 | 0.794196 | 0.983347 | 0.992441 | 0.996351 | 0.999061 |
| Guitar | 0.198769 | 0.549556 | 0.761197 | 0.865428 | 0.958670 |
| Guitar \textbf{\textit{p}} | 0.198769 | 0.446254 | 0.606756 | 0.751304 | 0.928321 |
| Guitar \textbf{\textit{f}} | 0.268161 | 0.772095 | 0.856637 | 0.900786 | 0.958670 |

In [24]:
```
r2_stats.style.to_latex(GFX_PATH / '1-r2-stats.tex', hrules=True,
                        label='tab:r2-stats',
                        caption=r'\(R^2\) scores of the deterministic synthesis, in quantiles.',
                        position_float='centering')
```

```
ALSA lib pcm.c:8545:(snd_pcm_recover) underrun occurred
```

Copying the analysis results that are referenced in the report...

In [25]:
```
def write_results(df, fname):
    asig = pya.Asig(str(df.loc[fname + '.mp3'].clipped_wav))
    asig.save_wavfile(str(WAVS_PATH / ('ch3_' + fname + '_clipped.wav')))
    asig = pya.Asig(str(df.loc[fname + '.mp3'].resynth_wav))
    asig.save_wavfile(str(WAVS_PATH / ('ch3_' + fname + '_harmonic-analysis.wav')))
    asig = pya.Asig(str(df.loc[fname + '.mp3'].noise_wav))
    asig.save_wavfile(str(WAVS_PATH / ('ch3_' + fname + '_noise-residue.wav')))

for fname in [
    "cello_A4_15_forte_arco-normal",
    "cello_Cs3_15_fortissimo_arco-normal",
    "cello_Cs3_15_pianissimo_arco-normal",
    "cello_E4_15_mezzo-piano_arco-normal",
]:
    write_results(cello_df, fname)

for fname in [
    "guitar_As4_very-long_forte_normal",
    "guitar_Ds3_very-long_piano_normal"
]:
    write_results(guitar_df, fname)
```

```
ALSA lib pcm.c:8545:(snd_pcm_recover) underrun occurred
```