




1 QuasinormalModes.jl: A Julia package for computing 2 discrete eigenvalues of second order ODEs

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DOI: [10.21105/joss.04077](https://doi.org/10.21105/joss.04077)

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Submitted: 22 September 2021¹³

Published: 20 January 2022

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5 Summary

6 In General Relativity, when perturbing a black hole with an external field, or particle, the
7 system relaxes by emitting damped gravitational waves, known as *quasinormal modes*. These
8 are the characteristic frequencies of the black hole and gain the *quasi* prefix due to the fact
9 that they have a real frequency, which represents the oscillation frequency of the response, and
10 an imaginary frequency that represents the decay rate of said oscillations. In many cases, such
11 perturbations can be described by a second order homogeneous ordinary differential equation
12 (ODE) with discrete complex eigenvalues.

Determining these characteristic frequencies quickly and accurately for a large range of models
is important for many practical reasons. It has been shown that the gravitational wave signal
emitted at the final stage of the coalescence of two compact objects is well described by
quasinormal modes ([Buonanno et al., 2007](#); [Seidel, 2004](#)). This means that if one has access to
a database of quasinormal modes and of gravitational wave signals from astrophysical collision
events, it is possible to characterize the remnant object using its quasinormal frequencies.
Since there are many different models that aim to describe remnants, being able to compute
the quasinormal frequencies for such models in a reliable way is paramount for confirming or
discarding them.

22 Statement of need

23 QuasinormalModes.jl is a Julia package for computing the quasinormal modes of any
24 General Relativity model whose perturbation equation can be expressed as second order ho-
25 mogeneous ODE. Not only that, the package can be used to compute the discrete eigenvalues
26 of *any* second order homogeneous ODE (such as the energy eigenstates of the time inde-
27 pendent Schrödinger equation) provided that these eigenvalues actually exist. The package
28 features a flexible and user friendly API where the user simply needs to provide the coefficients
29 of the problem ODE after incorporating boundary and asymptotic conditions on it. The user
30 can also choose to use machine or arbitrary precision arithmetic for the underlying floating
31 point operations involved and whether or not to do computations sequentially or in parallel
32 using threads. The API also tries not to force any particular workflow on the users so that
33 they can incorporate and adapt the existing functionality on their research pipelines without
34 unwanted intrusions. Often user friendliness, flexibility and performance are treated as mu-
35 tually exclusive, particularly in scientific applications. By using Julia as an implementation
36 language, the package can have all of these features simultaneously.

37 Another important motivation for using Julia and writing this package was the lack of
38 generalist, free (both in the financial and license-wise sense) open source tools that serve the
39 same purpose. More precisely, there are tools which are free and open source, but run on top
40 of a proprietary paid and expensive software framework such as ([Jansen, 2017](#)) and ([Fortuna](#)

& Vega, 2020), which are both excellent packages that aim to perform the same task as `QuasinormalModes.jl` and can be obtained and modified freely but, unfortunately, require the user to own a license of the proprietary Wolfram Mathematica CAS. Furthermore, their implementations are limited to solve problems where the eigenvalues must appear in the ODE as a polynomials of order p . While this is not prohibitively restrictive to most astrophysics problems, it can be an important limitation in other areas. There are also packages that are free and run on top of Mathematica but are not aimed at being general eigenvalue solvers at all, such as (O'Toole et al., 2019), that can only compute modes of Schwarzschild and Kerr black holes. Finally, the Python package (Stein, 2019) is open source and free but can only compute Kerr quasinormal modes.

`QuasinormalModes.jl` fills the existing gap for free, open source tools that are able to compute discrete eigenvalues (and in particular, quasinormal modes) efficiently for a broad class of models and problems. The package was developed during the author's PhD research where it is actively used for producing novel results that shall appear on the author's thesis. It is also actively used in a collaborative research effort (of which the author is one of the members) for computing quasinormal modes produced by perturbations with integer (but different than 0) spins and semi-integer spins. These results are being contrasted with those obtained by other methods and so far show excellent agreement with each other and with literature results.

Underlying algorithm

`QuasinormalModes.jl` internally uses a relatively new numerical method called the Asymptotic Iteration Method (AIM). The method was introduced in (Ciftci et al., 2003) but the actual implementation used in this package is based on the revision performed in (Cho et al., 2012). The main purpose of the (AIM) is to solve the following general linear homogeneous second order ODE:

$$y''(x) - \lambda_0(x)y'(x) - s_0(x)y(x) = 0, \quad (1)$$

where primes denote derivatives with respect to the variable x (that is defined over some interval that is not necessarily bounded), $\lambda_0(x) \neq 0$ and $s_0(x) \in C_\infty$. The method is based upon the following theorem: let λ_0 and s_0 be functions of the variable $x \in (a, b)$ that are C_∞ on the same interval, the solution of the differential equation, Eq. (1), has the form

$$y(x) = \exp\left(-\int \alpha dt\right) \times \left[C_2 + C_1 \int^x \exp\left(\int^t (\lambda_0(\tau) + 2\alpha(\tau))d\tau\right) dt\right] \quad (2)$$

if for some $n > 0$ the condition

$$\delta \equiv s_n \lambda_{n-1} - \lambda_n s_{n-1} = 0 \quad (3)$$

is satisfied, where

$$\lambda_k(x) \equiv \lambda'_{k-1}(x) + s_{k-1}(x) + \lambda_0(x)\lambda_{k-1}(x) \quad (4)$$

$$s_k(x) \equiv s'_{k-1}(x) + s_0\lambda_{k-1}(x) \quad (5)$$

where k is an integer that ranges from 1 to n .

Provided that the theorem is satisfied we can find both the eigenvalues and eigenvectors of the second order ODE using, respectively, Eq. (3) and Eq. (2). Due to the recursive nature of Eq.(4) and Eq.(5), to compute the quantization condition, Eq.(3), using n iterations the n -th derivatives of λ_0 and s_0 must be computed multiple times. To address this issue, (Cho et al., 2012) proposed the use of a Taylor expansion of both λ and s around a point ξ where the AIM is to be performed. This improved version is implemented in `QuasinormalModes.jl`

Benchmark

To show `QuasinormalModes.jl` in action, this section provides a simple benchmark where the fundamental quasinormal mode ($n = \ell = m = s = 0$) of a Schwarzschild black hole was computed using 16 threads on a Intel(R) Core(TM) i9-7900X @ 3.30GHz CPU with 256 bit precision floating point numbers.

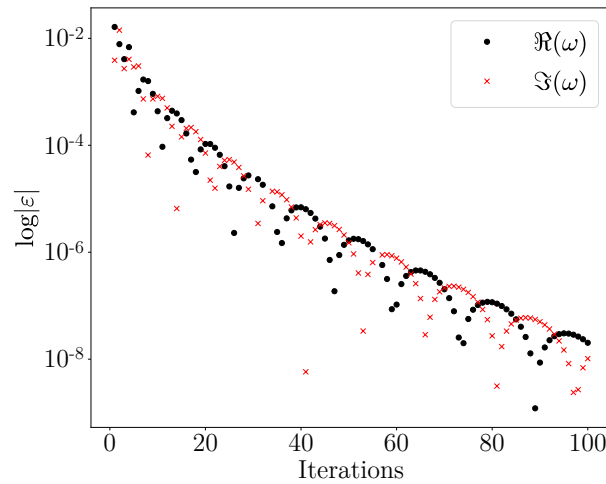


Figure 1: Error convergence for the fundamental Schwarzschild quasinormal mode as a function of the number of AIM iterations.

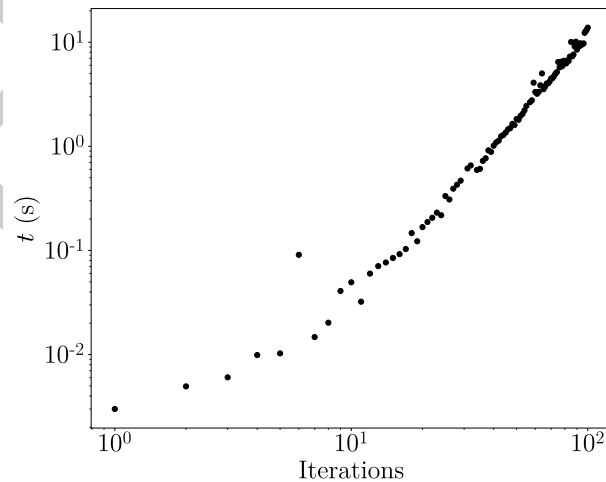


Figure 2: Time taken to compute the fundamental Schwarzschild quasinormal mode as a function of the number of AIM iterations on a logarithmic scale.

In order to quantify the rate at which the method converges to the correct results, the error measure ε was defined as follows: given the computed real and imaginary quasinormal frequencies, denoted respectively by ω_R and ω_I , and the reference frequencies given in (Berti et al., 2009), denoted respectively as $\bar{\omega}_R$ and $\bar{\omega}_I$ we have that $|\varepsilon| = |\omega_{R,I} - \bar{\omega}_{R,I}|$. In Figure 1 ε is plotted as a function of the number of iterations for both the real and imaginary frequencies. We can see that, as the number of iterations increases, the error in the computed values rapidly decreases.

In Figure 2, the time required to perform a certain number of iterations is plotted in logarithmic scale. Each data point is the arithmetic mean time obtained after 10 runs of the algorithm for a given number of iterations. The time measurement takes care to exclude the overhead induced at “startup” due to Julia’s JIT compilation. Even though the time taken to perform a certain number of iterations increase with a power law, the time scale required to achieve highly accurate results is still around 10s. This time would be even smaller if one chooses to use built-in floating point types instead of arbitrary precision numbers.

Acknowledgements

I would like to thank Iara Ota for the helpful comments, discussions and revision of this paper. This research was supported by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES, Brazil) - Finance Code 001

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