ORIGIN OF THE RESPONSE SPECTRUM METHOD

M.D. Trifunac[1] and M.I. Todorovska[2]

[1] *Prof., Dept. of Civil Engng., Univ. of Southern Caliornia, Los Angeles, CA 9089, U.S.A.*
[2] *Res. Prof., Dept. of Civil Engng., Univ. of Southern California, Los Angeles, CA 9089, U.S.A.*
Email: trifunac@usc.edu, http://www.usc.edu/dept/civil_eng/Earthquake_eng/

ABSTRACT :

Writing about the early history and formative ideas of a given subject helps in documenting what is known, and in searching for the key factors that have led to the formulation of a new concept. History teaches us about the key players, their teachers, and the times in which they lived—and leads us to discover the anatomy of the process that led to the new ideas. Today, when we study a broad spectrum of natural and societal phenomena, it is only natural and logical to try to research also the origins and the conditions surrounding the development of a significant new concept. In the following, we outline the early history of the response spectrum method. We discuss the vibrational versus wave methods of solution, and examine the consequences this had on the earthquake engineering profession.

KEYWORDS: History of earthquake response spectrum, history of earthquake engineering.

1. INTRODUCTION

The period from 2007 to 2009 marks the 75th anniversary of the mathematical formulation of the concept of the response spectrum method (RSM), which began in 1932, in the doctoral dissertation of M.A. Biot (1905–1985). Since then, the RSM has evolved into a principal tool and the central theoretical framework—a conditio sine qua non—for Earthquake Engineering. The RSM remained in the academic sphere of research for many years and did not gain widespread engineering acceptance until the early 1970s. There were two main reasons for this. First, the computation of the response of structures to earthquake ground motion led to “certain rather formidable difficulties” (Housner 1947), and, second, there were only a few well-recorded accelerograms that could be used for that purpose. This started to change in 1960s with the arrival of digital computers and the commercial availability of strong-motion accelerographs (Trifunac 2007a). Before the digital computer age, the computation of structural response was time consuming, and the results were unreliable (Trifunac 2003). By the late 1960s and early 1970s, the digitization of analog accelerograph records and the digital computation of ground motion and of the response spectra were developed completely and tested for accuracy. Then, in 1971, with the occurrence of the San Fernando, California, earthquake, the modern era of RSM was launched. This earthquake was recorded by 241 accelerographs, and by combining these data with all previous strong-motion records it became possible to perform the first comprehensive empirical scaling analyses of response spectral amplitudes (Lee 2002).

The early history of the development of the RSM has been outlined in several recent publications (e.g. Trifunac 2007b) and will be summarized here only for the completeness of this presentation. Our focus in this paper will be to examine the background and the reasons for the prevailing vibrational approach to the solution of the earthquake response problem. The description of the more recent developments in the RSM are beyond the scope of this work. The reader can find papers on the contemporary uses of the RSM in the special issue of the *Indian Society of Earthquake Technology (ISET) Journal*, Vol. 44. No. 1, published in 2007.

2. ENGINEERING MECHANICS BEFORE THE EARLY 20TH CENTURY

The solution of the differential equations that describe the dynamic response of structures can be formulated in terms of waves (D’Alembert (1717–1783) first described this method of solution in a memoir of the Berlin Academy in 1750), or using a vibrational approach in terms of the characteristic functions (mode shapes) (Bernoulli (1700–1782), first wrote about this method in a memoir of the Berlin Academy in 1755). The related problem of the vibrating string was solved analytically by Lagrange (1736–1830) in a memoir of the Turin Academy in 1759, which established the existence of a number of independent frequencies equal to the number of interconnected particles. Mathematical principles and the methods associated with the latter approach have been further researched and described extensively by Rayleigh (1842-1919) in his *Theory of Sound,* first published in England in 1877.

Rayleigh's interest in acoustics was initiated with the advice of professor W.F. Donkin, at Oxford, to learn to read German. Rayleigh did so and then read Helmholtz's treatise *Lehre von der Tonenpfindung,* which lead to his first paper on the theory of resonance in 1870. Shortly after his marriage to Evelyn Balfour in 1871, a serious attack of rheumatic fever weakened Rayleigh's health. As a recuperative measure, during late 1892, he took a trip up the river Nile in Egypt. The first part of the *Theory of Sound* had its genesis during this trip, on a house-boat, and without access to a large library. The first edition of the *Theory of Sound* appeared in June 1877. Its first volume is devoted to vibrations of the dynamic systems, with emphasis on the subjects dealing with acoustics. However, the first ten chapters outline the methods and theory, which are relevant and can be applied to most vibrating systems encountered in practice. In the first volume, Rayleigh addresses the wave solution of the governing equations, but emphasizes the vibrational approach. *Theory of Sound* opens with the treatment of the oscillations of a system with one degree of freedom. Then follow two chapters on the general theory of vibrations of *n*-degree-of-freedom systems, where Rayleigh emphasizes the value of approximating the lowest frequency of vibration of a complicated system, for which the solution is impracticable. He makes use of the expressions for maximum potential and kinetic energies, the method later generalized by Ritz, and now known as Rayligh-Ritz method. Throughout his work Rayleigh displays preference for the use of the energy considerations and for virtual work, and often derives the differential equations of vibrating systems using the energy approach. Perusal of the text-books on the mathematical methods in engineering from the early 20th century will show how influential was this Rayleigh's approach for solving the vibration problems. For example, in the text *Mathematical Methods in Engineering* (von Kármán and Biot 1940), which during 1940s and 1950s served as one of the principal texts for many engineers in America, who later became active in earthquake engineering, chapter V, which deals with oscillations of conservative systems, uses and extends the Rayleigh's energy methods, and solutions in terms of characteristic functions. In Europe, the works of van den Dungen (1926, 1928), and Hohenemster (1932) described analogous methods for solving vibrations problems in terms of characteristic functions.

It is not surprising then that in his formulation of the response spectrum method Biot also chose the vibrational representation of the solution, in which each mode shape and its natural frequency are associated with one equivalent single-degree-of-freedom (SDOF) system. For linear systems the response is then represented as a superposition of the responses of those equivalent SDOF systems. The analysis of the linear response of an *n*-degree-of-freedom system is thus reduced to a study of individual SDOF systems, one at a time.

2.1 Early Dynamic studies

The Messina and Reggio Calabria earthquake of 1908, in Italy, made a strong impression on Italian engineers. Panels were formed to search for earthquake resistant construction methods (Giuffrè 1987), and, in response to several professional competitions, papers were presented on the analyses of building response to ground shaking (Sorrentino 2007). Among those, was the work of Arturo Danusso (1880-1968), who presented one of the first applications of the dynamic principles to earthquake response of structures. Italian engineers started with the assumption that any dynamical analysis would be impractical in earthquake resistant design, and recommended an approximate design approach in terms of equivalent static force. This simplified procedure persisted in Italy until 1975 (Di Pasquale et al. 2000).

Danuso observed that the forces in a structure are not governed only by the acceleration of the ground, but depend also on the "elastic flexibility of the building skeleton". He further states that "To cut as much as possible this [seismic] energy which will be transferred to the construction"…..can be accomplished by letting the building "follow docile the shaking action, not opposing it stiffly" (Danusso 1909). Danusso's structural models were made of columns with no mass, and all building mass was concentrated at floor levels (Sorrentino 2007). He wrote dynamic equilibrium equations, and studied response of single and two degree of freedom systems to sinusoidal representation of ground motion (first strong motion accelerations were recorded in 1933, during Long Beach earthquake in California, 22 years later; Trifunac 2008). In contrast to Rayleigh (1877, 1945), who obtained the equations of motion using potential and kinetic energies, in a Lagrangian formulation, Danusso used the D'Alembert's principle, and considered no damping. However, as Rayleigh, Danusso used vibrational approach to solve the governing differential equations, and notes that "[it] is easy to recognize in the motion of any mass of an *n*-tuple pendulum a linear combination of the motions of n simple pendulums" (Danusso 1928, Sorrentino 2007). Perhaps because he published in Italian, Danusso's work had small international influence. Freeman (1932) does mention Danusso's work, but "there is no evidence that von Karman and Biot had any knowledge" of it (Sorrentino 2007).

In other countries the early earthquake engineering research also started to evolve following major earthquake disasters. For example, in California, following the 1906 San Francisco earthquake (Freeman 1932, Geschwind 1996, Reitherman 2006), and in Japan following the 1923 disaster in Tokyo (Suyehiro 1932).

2.2 Theodore von Kármán and Maurice Biot

The mathematical formulation of the RSM first appeared in the doctoral dissertation of M.A. Biot in 1932 and in

At Professor von Kármán's House in Pasadena.

two of his papers (Biot 1932a, 1933, 1934a). Biot defended his Ph.D. thesis at Caltech in June 1932 (Biot 2007a) and presented a lecture on the method to the Seismological Society of America meeting, held at Caltech, the same month. Theodore von Kármán (von Kármán and Edson 1967), Biot's advisor, played the key role in guiding his student and in promoting his accomplishments. After the method of solution was formulated, Biot and von Kármán searched for an optimal design strategy. A debate at the time was whether a building should be designed with a soft first floor or be stiff throughout its height, to better resist earthquake forces. An excerpt from the *New York Herald Tribune* in June 1932 illustrates this:

Shock Proof Buildings Sought by Scientists. Rigid or Flexible Materials, Their Difference in Theory

A building proof against earthquakes is the goal of Dr. Theodor von Kármán and Dr. M. Biot, of the California Institute of Technology. Dr. von Kármán described to the American Society of Mechanical Engineers, whose convention was held recently at Yale, studies of the amount of shock, which various types of buildings have undergone in Japan, South America, and California. Their researches are being conducted at the Institute's Guggenheim Aeronautical Laboratory.
One of the principal problems is to decide whether a rigid or flexible structure is better. Some scientists contend the first is preferable; others would make the ground floor of tall buildings flexible.
Pointing out that the reinforced concrete is superior to steel in absorbing the shocks, Dr. von Kármán's personal belief is that the building should be constructed to shake "with the rhythm of the earth's movements."

Biot's interest in the maxima of the transient response in solids and in fluids preceded (Biot 1932b), and extended beyond, earthquake engineering (Biot 1934b). After he formulated the concept of the RSM, he extended it to other vibrational problems such as the analysis of aircraft landing gear (Biot and Bisplinghoff 1944). He briefly returned to the subject of earthquake engineering almost ten years later, presenting response spectral amplitudes of several earthquakes, which he calculated using a torsional pendulum at Columbia University (Biot 1941). In 1942 he presented a review of the response spectrum method (Biot 1942), discussed the effects of flexible soil on the rocking period of a rigid block (Biot 2006), and described again the spectrum superposition method based on the sum of absolute modal maxima. After 1942, Biot moved on to other subjects, making fundamental contributions to many other fields (Biot 1965, 1970, Tolstoy 1992). He did not write papers on earthquake engineering (Trifunac 2005a), but followed closely and with interest the work of others (Biot 2007b).

The principal areas of Biot's opus, and his technical views have been described by Mindlin (1989) and by Tolstoy (2006). A complete list of Biot's publications can be found in Trifunac (2006a), and a list of his patents and awards is contained in the introduction to Vol. 14 of the *Journal of Mathematical and Physical Sciences*, published in Madras, India, in 1980, on the occasion of his seventieth birthday anniversary. Biot's early education in England, France, and Belgium, and his work during World War II, are described in a brief biographical sketch written by his wife Nady Biot (2007a).

In spite of Biot's seminal contributions to earthquake engineering, his work is rarely cited by earthquake engineers (Trifunac 2005a). In part this may be an indirect consequence of the fact that about 78 percent of all journal papers published in the field of Civil Engineering are never cited, and because many earthquake engineering authors include only small number of references in their journal papers, with emphasis on the more recent work (Trifunac 2005b, 2006b). Nevertheless, more than 20 years after his death, in 1985, Biot is one of the most cited authors in applied science, especially in the subject of poromechanics. The conventional wisdom is that citations are the glue that bonds a research paper to the body of knowledge in a particular field and are a measure of the paper's importance. Thus, a careful analysis of citations can offer all earthquake engineers a great deal to think about. Citations are also a vehicle that places our profession into the historical framework of the field and shows how the ideas and methods evolve (Tifunac 2005c).

2.3 Response Spectrum Method

In Biot (1934a), on page 213, he states that "any vibration of an elastic undamped system may always be considered as a superposition of harmonics." Few lines further down, he continues: "…[a] building, like any elastic system, has a certain number of so called *normal modes* of vibration, and to each of them corresponds a certain frequency…we will show that any motion can be calculated when we know these modes of vibration." On the next page, Biot defines F(v), which he calls the *frequency distribution* or the *spectral distribution* of ground acceleration—which in our modern terms is the Fourier amplitude spectrum of ground acceleration. Near the bottom of the same page, Biot states:

> …we are not interested in the motion itself of the building, but merely in its maximum amplitude. This maximum is the sum of the amplitudes of each separate free oscillation. It will not always be reached because it supposes that an instant exists for which all of the free oscillations have their maximum deflection simultaneously. However, this maximum will many times be nearly reached in a short time, and in any case it is the highest possible value.

(Today we refer to this vibrational formulation of the RSM as *Biot's sum of absolute maxima*—e.g., Amini and Trifunac 1985). Finally, on page 215, Biot discusses the properties of the *spectral distribution*, and mentions Suyehiro's observations in Japan. He then concludes: "If we possessed a great number of seismogram spectra we could use their envelope as a standard spectral curve for the evaluation of the probable maximum effect on buildings."

The above summarizes Biot's formulation of the response spectrum method and of response spectrum superposition concept. Physically and mathematically it can be argued that it is superior to our modern use of the relative displacement or velocity spectra because it is directly related to the description of ground motion, via the Fourier amplitude spectrum, F(v), of strong motion acceleration. However, for all practical purposes, the modern procedures are equivalent to Biot's formulation because of close agreement between the amplitudes of F(v) and of the true relative velocity spectra, and because the amplitudes of true velocity spectra and pseudo velocity spectra are also practically the same (Hudson 1956).

The terminology used in connection with the response spectrum concept has been evolving since 1932. Different scaling functionals were considered and used by those writing the papers on this subject during 1930s (energy spectra, spectral intensity curves, etc., Benioff 1934), and others, who worked with the torsional pendulum (Neumann 1936, 1937; Savage 1939) or with the models of buildings on a shaking table (Jacobsen at Stanford), were also doing essentially the same thing—computing the relative displacement response spectra—even when they called it by different names.

From mid- to late 1930s, Von Kármán and Biot were writing their book *Mathematical Methods in Engineering* (McGraw-Hill 1940) (Biot 2007a), which had several chapters directly applicable to the structural dynamics problems related to earthquakes (Hudson 1997). As graduate students Biot, Housner, Hudson, Popov (EERI 2002), and many others all took courses from von Kármán (Trifunac 2007b), whose style of teaching, with emphasis on the essential physical nature of the problem, left a strong and enduring impression. In EERI (1997) Housner recalls, "when I started to work on my Ph.D. thesis on the dynamics of buildings, Prof. Martel asked von Kármán about the differential equation for a vibrating beam."

2.4 Response spectrum in design

In his 1934a paper, Biot stated that if a large enough number of seismogram spectra were available it would be possible to use their envelope as a standard spectral curve for evaluating the probable maximum effect on structures. In Biot (1941), he continued: "These standard curves…could be made to depend on the nature and magnitude of the damping and on the location. Although the previously analyzed data do not lead to final results, we…conclude that the spectrum will generally be a function decreasing with the period for values of the latter greater than about 0.2 s. A standard curve for earthquakes of the Helena and Ferndale…for values T > 0.2 s, could very well be the simple hyperbola $A = 0.2g/T$, and for $T < 0.2$ s, A = g (4T + 0.2), where T is the period in seconds and g the acceleration of gravity. Whether this function would fit other earthquakes can only be decided by further investigations."

The rapid increase in the number of recorded strong motion accelerograms, which started with San Fernando earthquake, in California, in 1971, made possible advanced and more complete empirical scaling of the response spectral amplitudes. Detailed review of this subject is beyond the scope of this paper, but the reader can find a detailed review in Lee (2002).

The development of current seismic building code provisions in California started in the 1950s. A Joint Committee of the San Francisco Section of the ASCE and the Structural Engineers Association of Northern California prepared a "model lateral force provision" based on a dynamic analysis approach and response spectra (Anderson et al. 1952, EERI 1996). The Proposed Design Curve, $C = K/T$, was based on a compromise between a standard acceleration spectrum by Biot (Biot 1941,1942) and an El Centro analysis by E.C. Robison. The Biot curve for peak ground acceleration (PGA) of 0.2 g has a peak spectral acceleration of 1.0 g at a period of 0.2 s. The curve then descends in proportion to 1/T. If the peak spectral acceleration is limited to 2.5 times the PGA, the Biot spectrum is very close to the 1997 UBC design spectrum for a PGA of 0.2 g. The proposed design lateral force coefficient was $C = 0.015/T$, with a maximum of 0.06 and a minimum of 0.02. These values were considered consistent with the current practice, and the weight of the building included a percentage of live load (Freeman 2007).

2.5 Contemporary role of the Response Spectrum Method

As the purpose of this writing is to focus on the early history in the development of the response spectrum method and on its vibrational nature, a review of its modern developments and uses is well beyond the present scope. Nevertheless, towards completeness of this presentation, we mention a few topics and cite several sources that can help by providing some linkage of this work with the contemporary uses of the method.

Biot viewed the formulation of the standard design spectra as an enveloping process that depended upon the availability of many accelerograms recorded under different earthquake and site conditions (see Biot 1934a). This approach was used extensively in numerous projects requiring site-specific design criteria, and it has also been responsible for influencing the spectral shapes used in design codes (Freeman 2007). After the mid-1970s, with the accumulation of the recorded and processed strong-motion accelerograms, and following the development of the concept of uniform hazard spectrum in 1977 (Gupta 2007), Biot's concept of searching for envelopes evolved into a process of finding the distribution functions of site-specific spectral amplitudes. After the detailed distribution functions of spectral amplitudes were developed (Lee 2002), it became possible to use the uniform hazard spectrum in both site-specific work and in seismic microzonation (Gupta 2007).

Other developments contributed to (1) better understanding of and refinement in the selection of the peaks of the relative response of structures (studies using order statistics for estimation of the largest peaks—e.g., Gupta and Trifunac 1988), (2) proposals on how to use the response spectrum method in the presence of soil-structure interaction (Gupta and Trifunac 1990), and (3) the generalization of the response spectrum method for long structures, which are sensitive to differential amplitudes of strong ground motion. (e.g., Gičev and Trifunac 2006; Jalali et al. 2007, Jalali and Trifunac 2007a,b).

3. CONCLUSIONS

Further study of numerous contributions to the subject of the response of structures to earthquake ground shaking will show almost universal preference for the vibrational approach to the solution of this problem. The vibrational approach has become so pervasive and so universally accepted that with almost no exceptions the authors do not even comment on the reasons for their choice of this solution method. An interesting aspect of this situation is that even in the more recent papers, which claim to deal with the performance based design, and which should aim for more realistic and physically more representative modeling of the response problem, the classical lumped mass representations of n-degree-of-freedom systems, and mathematical formulations in terms of characteristic functions, even for nonlinear problems, still govern the modus operandi. The formulations of Lagrange, and Rayleigh, which were adopted for earthquake engineering applications by the pioneers of early 20th century (Danusso, von Kármán and Biot), and by their many followers, and students, who during the mid 20th century contributed to the earthquake engineering field as we know it today, still prevail with remarkably little change. It is a matter of time before the profession will recognize that the wave propagation method of solution offers far more realistic tools to predict the location and the nature of the damage caused by large near field earthquake pulses (Gičev and Trifunac 2007). However, considering the typical scope of even the most advanced engineering graduate programs in the leading universities this process of change will probably take long time.

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