

Memoir for the 50th Anniversary volume of the JMES

MECHANICAL VIBRATION: R. E. D. BISHOP'S CONTRIBUTION TO THE JMES

by

D E Newland
Cambridge University Engineering Department
Trumpington Street
Cambridge
CB2 1PZ
den@eng.cam.ac.uk

Preamble

Vibration analysis and control has been one of the principal themes of the JMES since its inception. The Journal's first issue contained four papers on vibration topics. Three of



these had R E D (Dick) Bishop as author or co-author (1, 2, 3). All were on the subject of rotor vibration and balancing. The fourth was by R F Henry and S A Tobias on a nonlinear vibration problem (4). That theme has continued throughout the 50-year history of the Journal and Dick Bishop played a large part in establishing the JMES as an accepted forum for good papers on mechanical vibrations. He was one of the founding members of the JMES's editorial panel and remained so for 30 years before his untimely death in 1989. I have been asked to write about Dick's contribution to the JMES and the outcome of his work. The photo shows him in typical pose at a dinner in Cambridge in 1978.

Early history

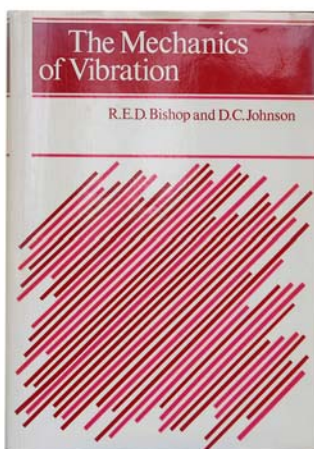
The half-century since the first issue of JMES was published in 1959 now covers fully half the lifetime of vibration theory as a separate discipline within mechanical engineering. S P Timoshenko, a Russian who emigrated to the USA in 1922 when aged 44, was the founding father. Essentially a distinguished applied mathematician, Timoshenko had a good grasp of contemporary vibration problems and he was an energetic and prolific author and a charismatic research supervisor. Bishop studied under Timoshenko at Stanford University in the 1950s and, not surprisingly, Dick Bishop's first paper in the JMES draws on material in Timoshenko's book, *Vibration Problems in Engineering* (ref. (5), by then in its 3rd edition). The publication of that book in 1928, by such an already well-known and distinguished figure in the developing field of applied mechanics, established mechanical vibration as a subject for serious study in its own right.

Another emigrant to the USA in the 1920s was the Dutchman J P Den Hartog. He and Timoshenko both worked for Westinghouse, in the same research department at Pittsburgh, before each left for a career in academia. Den Hartog became the leading practitioner of vibration theory, with a worldwide reputation, working first at Harvard University and then at MIT. I do not know the circumstances that led to him being invited to lecture to the Institution, but Den Hartog gave the 1956 Thomas Hawksley lecture on the subject of mechanical vibration (6) and he and Dick Bishop were well acquainted. Den Hartog's book (7) *Mechanical Vibrations*, by 1959 in its 4th edition, is also referred to by Dick Bishop in that first JMES paper.

Dick was appointed to an assistant lectureship (then called a demonstratorship) in the Cambridge University Engineering Department, where he became a close colleague of D C (Dan) Johnson. D. C. Johnson had joined the Cambridge department in the same capacity after the war in 1946. Although it was a time of austerity, with record numbers of undergraduates returning from war service, their department encouraged research. What's more, staff were given the time to do it (no research assessments to worry about, no constant battle for research funding), and these two like-minded young staff members flourished.

They were able to build on the work at Cambridge of a former President of the Institution, C E Inglis, and at Bristol by W J Duncan. Duncan had obtained good results by using a frequency-response approach in his study of propeller-driven aircraft. Bishop and Johnson knew of this approach and worked together, initially on calculating the frequency response of many linear dynamical systems, of increasing complexity. They used the name receptance for what vibration and control engineers now think of as a frequency-response function. The name "receptance" apparently dates from discussions in 1954 between W J Duncan, M A Biot, D C Johnson and R E D Bishop. Their reason for choosing a new name appears to have been because the term "mechanical admittance", which was then popular, was causing confusion because of its customary alternative use in electrical engineering.

Theoretical analysis of the dynamics of flexible rotors



The main permanent result of the Bishop-Johnson collaboration is their 600 page volume *The Mechanics of Vibration* (9), completed in 1957 (although not published until early 1960). This collaborative effort was made more difficult when D C Johnson was appointed to a chair at Leeds in 1956 and then R E D Bishop to the Kennedy Chair at University College London in 1957, and both assumed wider responsibilities than their own research.

By the time of the first issue of the JMES, Dick Bishop had published some 30 papers covering an interesting range of vibration problems, mainly linear vibration and wave propagation topics, but so far nothing on rotating shafts. That

was about to change. Following his first rotating shaft paper, *The Vibration of Rotating Shafts* (1), in the first issue of this Journal, in the next 10 years, Bishop would be author or co-author of 10 more papers on the vibration and balancing of rotating systems (6 of them in the JMES), all written with his collaborators at the time, three more with G M L Gladwell, six with A G Parkinson and one each with A L G Lindley and S Mahalingam. In all, he published 23 more papers in the JMES.

Bishop and his co-workers developed what became known as the *modal method* for balancing large rotating systems like steam turbines and turbo-alternators. The importance of these papers is not so much for the method itself, important though this was as one of the first practical examples of modal analysis. The long-term significance of these papers lies in their rigorous approach to a difficult problem in applied mechanics, to which, at the time, only rudimentary theory had been applied. Contemporary balancing methods were experiencing increasing practical difficulty when trying to balance large rotating machines. Methods that had been proved effective for substantially rigid rotors, could not balance large flexible rotors successfully. The problem was that, as a rotor's speed approached a critical speed, natural shaft deflection altered the rotor's unbalance. And, paradoxically, rotors that had had balance weights added to achieve good balance at low speeds, would sometimes vibrate more at higher speeds than those which had not been balanced at low speeds. The modal balancing technique described in the papers by Dick Bishop and his collaborators overcame these disadvantages.

The discipline of rigorously developing dynamical equations, and then applying these to new problems in applied mechanics, was set for the Journal from its first issue. These three papers are very good examples of starting from first principles and applying the careful, painstaking and precise analysis that is the hallmark of a good paper in applied mechanics. As Bishop said in the first paper (1): "*To devise a theory of this sort, it is obviously necessary to start from first principles and, if possible, to keep all the steps in the subsequent development as simple as possible. The criterion of success in applied mechanics is one of adequacy, not of exactitude.*" Dick's series of papers on rotor dynamics in the JMES are very good examples of the author practising what he preached.

During the first 15 years of the journal, R E D Bishop and his collaborators published also on other subjects in the JMES, mainly on theoretical problems of linear vibration, on resonance testing, and on modal analysis. But, by 1974, Dick's interest had turned to ocean engineering and the dynamics of ships. This led him to publish mainly in marine journals and he only published four more JMES papers, one with S Mahalingam, one with I F A Wahed and two with his new collaborator W G Price on the dynamic analysis of marine structures.

But although he did not publish many more papers in the journal himself, Dick continued to promote the JMES with enthusiasm. He succeeded Hugh Ford as the third chairman of the Editorial Panel (the first was Own Saunders) and he continued in this capacity until his appointment as Vice-Chancellor of Brunel University in 1981.

Later developments

The JMES and its friendly rival journal, the International Journal of Mechanical Sciences, edited by Professor W (Bill) Johnson of UMIST, were both started together at a time of rapid change in applied mechanics. During the 30-year period of Dick Bishop's association with the JMES, there were major developments. In 1959, surprising though it may seem now, numerical results from digital computation were rare. Computers were hardly used. Much simulation was still done using analogue computers, with high-gain amplifiers in feedback loops modelling dynamic response. Digital computers were only just appearing in engineering laboratories, and they were hard to program.

There were exceptions and there was an important paper in Issue 1 by Dowson and Higginson (10) which included results calculated by digital computation. It gave a numerical solution for a problem in elasto-hydrodynamic lubrication, with results computed by the Leeds University Electronic Computing Laboratory. And, in Issue 2, there was a paper (11) by V Coldham of the firm English Electric (one of the original manufacturers of digital computers) who wrote that "*It is well known that electronic computers derive their usefulness from the ability to perform simple arithmetical operations at very high speed.*" But finite-element and boundary-element methods, which rely on massive number-crunching technology to make them practical computational methods were still to be perfected. Perhaps they have been the biggest single change in 50 years of the Journal. Access to huge FE and BE computational packages now provide the opportunity for computational insights into the behaviour of complex vibrating systems that were impossible 50 years ago.

And alongside this hugely increased power of computation has been a corresponding improvement in experimental methods. The development of miniature vibration transducers, and the improvement of instrument response by using charge amplifiers vastly improved the accuracy of experimental measurements. Then, in more recent years, the widespread adoption of digital data capture and processing had a huge effect. Together these developments revolutionised vibration and noise measurement.

This, in turn, led to the emergence of modal analysis as an essential tool for product design for vibration and noise environments. From the modal analysis of rotating shaft systems, which, although complicated, can be modelled by beam theory as described in Bishop's early papers, to the modal analysis of a structure like a motor car is a massive computational step. While the principles are the same, their implementation relies on being able to solve thousands of simultaneous equations. That could not be done without access to highly-developed finite-element computer programs. For the same reason, modelling the interaction between structural mechanical vibration and airborne acoustic vibration, which is now regularly a part of engineering analysis, could not be contemplated 50 years ago when the JMES started. And a feature of vibration control that took a long time to mature, because it depended on the introduction of micro-processors and digital control theory, but which has become an indispensable feature of vibration engineering, has been the introduction of control theory in active vibration control and in system synthesis.

Modern balancing methods

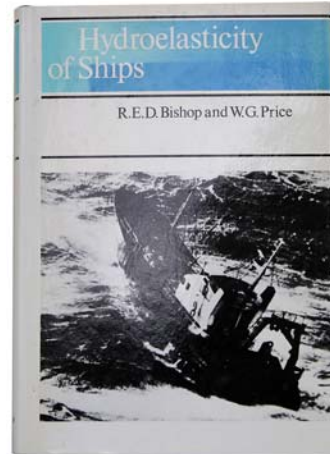
It is fascinating to explore how these developments have affected machine balancing, the subject of many of those early papers by Dick Bishop and his collaborators. Most industrial balancing of flexible rotors is now done by a combination of what at one time were regarded as two rival balancing procedures: the modal method of Bishop and colleagues and the so-called influence-coefficient method. In essence the latter is a trial-and-error approach in which test masses are added to a rotating system at different positions, and the resulting vibration measured at an array of measuring locations. However the choice of sensor locations for the influence-coefficient method is critical and it has to be guided by the results of a full modal analysis of the rotating system. So the best features of the two methods have been combined in a unified approach (34, 35). By assembling enough data, it is possible with modern technology to compute the position (and angular location) of balancing masses to reduce vibration from residual out-of-balance to acceptable levels at all operational speeds. This depends on the provision of a good measurement system and effective digital data analysis. Furthermore, in automatic in-service balancing, this process is automated by an active control system, so that balancing masses are moved according to whatever balancing strategy the designer intends. That was a process anticipated in a JMES paper by Van de Vegte (30) and which led to an immediate response by Dick Bishop, in what was to be his last JMES contribution (31).

These developments provide an interesting case history of how improvements in instrumentation and data handling and in active control have enabled substantial advances in balancing technology. The JMES has played its part in reporting these advances as they occurred. In 1990 there was a paper on automatically balancing flexible rotors (32) and in 1993 another on closed-loop vibration control of flexible rotors (33). And there have been many other papers in the Journal where the applications of intelligent materials and systems have greatly influenced our approach to the solution of engineering problems.

Postscript

Sadly, Dick Bishop did not live to see these developments. In the natural order, he would have been writing about the history of the JMES himself, but he died prematurely in 1989. I knew him well, having served as a fellow member of the JMES Editorial Panel for many years and having succeeded him as Chairman of the Panel when he retired from this post in 1981. His death left a void in his subject of Vibration and Dynamics. I and many of his collaborators over the years have greatly missed his incisive and challenging leadership in our branch of applied mechanics. He played a huge part in establishing the JMES as the respected and authoritative journal that it has become. There is a very good biography, prepared by Dick's friend and colleague Geraint Price, in a Royal Society memoir (36). It includes a full list of Dick's publications.

The list includes the book *Hydroelasticity of Ships* by Bishop and Price (37). This was complete as a manuscript in 1978. At the time, Dick's other book (8) had been allowed to go out-of-print by the Cambridge University Press, and he was unwilling to show them the manuscript for the new book unless they first undertook to reprint the old one. This CUP were reluctant to do. I found myself the intermediary between these two opposing forces, invited to comment on the new book for CUP but forbidden to reveal its full contents to them. Luckily a happy ending was achieved. Eventually *Mechanics of Vibration* was reprinted and CUP duly published *Hydroelasticity of Ships*, which is still in print nearly 30 years later.



References

- 1) Bishop, R. E. D. The vibration of rotating shafts. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **1**, 1959 (Issue 1), 50-65.
- 2) Bishop R. E. D. and Gladwell, G. M. L. The vibration and balancing of an unbalanced flexible rotor. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **1**, 1959 (Issue 1), 66-77.
- 3) Gladwell, G. M. L. and Bishop, R. E. D. The receptances of uniform and non-uniform rotating shafts. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **1**, 1959 (Issue 1), 78-91.
- 4) Henry, R. F. and Tobias, S. A. Instability and steady state coupled motions in vibration isolating suspensions. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **1**, 1959 (Issue 1), 19-29.
- 5) Timoshenko, S. P. *Vibration Problems in Engineering*. 3rd edition, 1955 (1st edition 1928), Van Nostrand Co., New York.
- 6) Den Hartog, J. P., *Vibration: a survey of industrial applications*. *Proc. IMechE.*, 1959, **172**, 8-27.
- 7) Den Hartog, J. P., *Mechanical Vibrations*. 4th edition, 1956 (1st edition 1934), McGraw-Hill, New York, now published by Dover Inc.
- 8) Bishop, R. E. D. and Johnson, D.C. *The Mechanics of Vibration*. 1960, Cambridge University Press.
- 9) Dowson, D. and Higginson, G. R. A numerical solution to the elasto-hydrodynamic problem. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **1**, 1959 (Issue 1), 6-15.
- 10) Coldham, V. Programming for electronic computation of stresses in piping systems. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **1**, 1959 (Issue 2), 93-102.
- 11) Gladwell, G. M. L. and Bishop, R. E. D. The vibration of rotating shafts supported in flexible bearings. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **1**, 1959, 195-206.
- 12) Gladwell, G. M. L. and Bishop, R. E. D. Interior receptances of beams. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **2**, 1960, 1-15.
- 13) Parkinson, A. G. and Bishop, R. E. B. Vibration and balancing of rotating continuous shafts. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **3**, 1961, 200-213.
- 14) Bishop, R. E. D. Note on a torsional failure caused by gear inaccuracy. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **4**, 1962, 188-198.

- 15) Parkinson, A. G., Jackson, K. L. and Bishop, R. E. D. Some experiments on the balancing of small flexible rotors: part 1 – theory. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **5**, 1963, 114-130.
- 16) Parkinson, A. G., Jackson, K. L. and Bishop, R. E. D. Some experiments on the balancing of small flexible rotors: part 2 – experiments. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **5**, 1963, 133-145.
- 17) Bishop, R. E. D. and Pendered, J. W. Note on resonance testing. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **5**, 1963, 343-344.
- 18) Pendered, J. W. and Bishop, R. E. D A critical introduction to some industrial resonance testing techniques. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **5**, 1963, 345-367.
- 19) Pendered, J. W. and Bishop, R. E. D. Extraction of data for a sub-system from resonance test results. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **5**, 1963, 368-378.
- 20) Pendered, J. W. and Bishop, R. E. D. The determination of modal shapes in resonance testing. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **5**, 1963, 379-401.
- 21) Parkinson, A. G. and Bishop, R. E. D. Residual vibration in modal balancing. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **7**, 1965, 33-39.
- 22) Bishop, R. E. D. and Parkinson, A. G. Choice of origin for body axes attached to a rigid vehicle. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **11**, 1969, 551-555.
- 23) Bishop, R. E. D. Harmonic displacement excitation at a support. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **14**, 1972, 1-3.
- 24) Mahalingham, S. and Bishop, R. E. D. Research note: reaction parameters for uniform beams subjected to displacement excitation. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **15**, 1973, 154-156.
- 25) Mahalingham, S. and Bishop, R.E. D. Research note: modal response to a specified transient acceleration. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **15**, 1973, 157-158.
- 26) Mahalingham, S. and Bishop, R. E. D. On the modification of subsystems in structural dynamics. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **17**, 1975, 323-329.
- 27) Bishop, R. E. D. and Price, W. G. Research note: a general method of structural analysis for marine structures and vehicles. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **17**, 1975, 363-365.
- 28) Wahed, I. F. A. and Bishop, R. E. D. On the equations governing the free and forced vibrations of a general non-conservative system. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **18**, 1976, 6-10.
- 29) Bishop, R. E. D. and Price, W. G. On the use of equilibrium axes and body axes in the dynamics of a rigid ship. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **23**, 1981, 243-256.
- 30) Van de Vegte, J. Balancing of flexible rotors during operation. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **23**, 1981, 257-261.
- 31) Bishop, R. E. D. On the possibility of balancing rotating flexible shafts. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, **24**, 1982, 215-220
- 32) Lee, Chong-Won, Joh, Young-Don and Kim, Young-Dae. Automatic modal balancing of flexible rotors during operation: computer controlled balancing head. *Proc. IMechE Part C: J. Mechanical Engineering Science*, **204**, 1990, 19-28..
- 33) Burrows. C. R., Keogh, P. S. and Tasaltin, R. Closed loop vibration control of flexible rotors. *Proc. IMechE Part C: J. Mechanical Engineering Science*, **207**, 1993, 1-18.
- 34) Muszyńska, Agnieszka (Agnes), *Rotordynamics*. 2005, Taylor & Francis, Boca Raton, FL, 2005.
- 35) Adams, Maurice L., Jr. Rotor balancing and unbalance-caused vibration. 2007, *Handbook of Noise and Vibration Control*, M. J. Crocker (ed). Wiley, New York, Ch. 62, 753-760.

- 36) Price, W. G., *Proc. R. Soc. Lond.*, 1994, Biographical Memoirs, 3-29.
37) Bishop, R. E. D. and Price, W. G. *Hydroelasticity of Ships*. 1979, Cambridge University Press.
-

D E Newland was a member of the Editorial Panel of the JMES from 1970-87 and Chairman of the Panel and Consultant Editor from 1981-87, following R E D Bishop's retirement from the chairmanship.